The System of Rice Intensification (SRI): Results from exploratory field research in Ivory Coast -- Research needs and prospects for adaptation to diverse production systems of resource-poor farmers

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Abstract

The *system of rice intensification* (SRI) has evolved in Madagascar during the 1980s and 1990s as an empirical practice and has been credited with spectacular grain yields. Subsequently, mostly on-farm tests have been conducted in Asian, Latin American and African countries, generally with promising results. This low-external-input system for rice is, however, still surrounded by many fundamental research questions in the bio-physical and agro-ecological domains.

From 1999 till 2001, WARDA conducted a series of exploratory field experiments in Ivory Coast to verify the potential and possible adaptation of SRI to West African conditions. This experimentation has involved considerable methodological challenges, because of the many – often confounded – production factors involved in such research.

A major conclusion has been that under conventional, irrigated (flooded) production systems, rice plants completed their development cycle prematurely, because of reduced growth and activity of the root system. Under the moist and aerated-soil conditions of SRI, the crop growth cycle was significantly extended, thereby creating a pre-condition for increased grain yields. Apart from changes in the soil moisture regime, other major crop production factors such as varieties and use of organic fertilisers, as well as *synergies* among factors, appear to be critical in optimising this low-external-input system. The results indicate ways forward for – rather basic – agricultural field research in support of developing low-external-input and environment-friendly technologies that may permit farmers to make attractive gains in productivity and in grain yield.

Keywords: rice production systems; low external input technologies; agro-ecological diversity; GxE interactions; system of rice intensification (SRI).

1. Introduction

The System of Rice Intensification (SRI) originated in the 1980s in Madagascar, in the Antsirabe region at ~1500m altitude. Here it has been adopted by a fair number of small farmers, who have obtained impressive yields, ranging from 6 to 15 tons/ha as compared with 2 to 3 tons with regular practices. Also elsewhere, notably in Asia (China, India, Indonesia, Sri Lanka, Bangladesh and Cambodia: see Uphoff *et al.*, 2002), the system has been tested with promising results. There are, however, also reports about farmers in Madagascar having recently abandoned the practice (Moser and Barrett, 2003).

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SRI still poses many fundamental questions and therefore, the explanations for adoption and disadoption are not very conclusive. Easy transfer of SRI is handicapped by a lack of knowledge about the processes and mechanisms that may contribute to the high yields. On the other hand, scientists (national and international) have been rather reluctant to look into the fundamental questions raised by SRI experience, many of which seem to go counter to conventional knowledge and concepts.

In Madagascar, the high yields were realised without the use of agricultural chemicals and on soils that are generally characterised as rather unfertile. The SRI method presumably compensates for the absence of external inputs through carefully timed and implemented practices. These are: very early transplanting of widely spaced, single seedings; regular weeding/soil cultivation, greatly reduced irrigation rates aimed at keeping the soil moist during the vegetative growth phase instead of continuously saturated, and liberal applications of organic manures (e.g. compost).

This article presents the results of exploratory trials conducted at WARDA in Ivory Coast from 1999 to 2001. The research was aimed at exploring the potential of SRI under West African conditions, and at clarifying some of the agro-ecological processes that might explain the high yields. The results question several conventional practices, but also some of the initially-identified – presumably critical – components of the SRI practice. The article concludes with a discussion of future research requirements to exploit a possible SRI potential fully in view also of the diverse needs of resource-poor farmers and the huge diversity in agro-ecological conditions under which rice is being cultivated.

2. Background and research hypotheses

The predominant concerns of both international and national agricultural research institutions have tended to be a form of *intensification* that involves the increased use of external inputs (mechanisation, mineral fertilisers and pesticides) together with high plant densities and high-yielding, modern varieties. The most successful of these varieties were often selected for their resistance against major pests and diseases (Conway and Toenniessen, 2003) and are mostly short-cycle, photoperiod-insensitive (100 to 120 days), as compared with the mostly photosensitive (140- to 150-day) local varieties used by many resource-poor farmers. The major objectives of this research have been to raise yields and labour productivity.

The modern varieties, however, appear to lack the ecophysiological traits that help produce high yields under the diverse agro-ecological conditions that are typical for resource-poor farmers, the major target group for the ongoing battle to reduce poverty. Since most of the external inputs involved in this kind of intensified production system are often too costly and/or are not available locally, research has to face the fact that resource-poor farmers will usually prefer different farming strategies, ones aiming primarily to increase factor productivity (particularly labor productivity). Resource-poor farmers therefore are likely to require technological options that are quite different from those that would be favored by large-scale commercial farmers (see also Stoop, 2002).

An initial review (Stoop *et al.*, 2002) concluded that under SRI, the basic crop production factors: *time, space, water, plant nutrients* and *labour* need to be considered simultaneously, and that responses might result largely from synergistic effects. Research into systems like

SRI therefore requires a holistic perspective. This confronts scientists with special challenges theoretically, as well as in terms of research methodology and its field implementation (Giller, 2000).

Two major plant features -- *tillering* and *root development* -- are postulated to be at the basis of the unusual yields under SRI. Tillering ability is genetically determined and positively correlated to maturity; it is also greatly affected by agronomic management practices like plant density and spacing (De Datta, 1981). The development of roots and tillers is interdependent and depends greatly on two basic production factors: *time* and *space.* The roles of these two factors need to be rethought, being crucial from an ecophysiological viewpoint by affecting the carbohydrate *source-sink* processes under markedly different growth-phenology-space-time relationships. This rethinking can be guided by the two concepts elaborated by Nemoto *et al.* (1995):

1. the *phyllochron* (a periodicity in plant growth expressed as the number of days to complete a unit of growth which produces one or more phytomers), and
2. the *phytomer* (the unit of plant growth in gramineae species, consisting of a leaf and subtending internode with a tiller bud at its base, and the ability to produce many adventitious roots unless internode elongation occurs).

These concepts contribute considerably in clarifying the dynamics of plant growth, and how shortening the phyllochron will accelerate growth, thereby increasing tillering and root development, while potentially shortening the crop maturity cycle. The implications of these concepts for SRI were discussed in Stoop *et al.* (2002).

If SRI is to realise its full potential, agronomic management must seek to maximise the tillering and rooting process per plant, presumably by optimising the conditions for the plant's early development through early transplanting, setting out single plants with wide spacing and regular early weeding. These measures that minimise inter- and intra-specific competition are combined with soil water management practices that create moist, aerated soil conditions through an irrigation regime of intermittent, greatly reduced rates. Together with the use of organic fertilisers (e.g. compost), a fundamentally different system is created as compared with continuously flooded systems.

Obviously, the entire dynamics of soil organic matter decomposition, and with it the activity of soil biota, the nutrient mineralisation processes for nitrogen, but also for other elements will be substantially altered (for phosphorus, see Turner and Haygarth, 2001). These considerations led to the formulation of three hypotheses that have guided the field studies:

1. The early vegetative development of the rice plant (i.e., during the first 4 to 6 weeks following seeding and the nursery and transplanting operations) is of far greater significance to the subsequent grain yield than has been assumed so far,
2. Rice cultivars will differ greatly in their respective capabilities to exploit the crop growth conditions associated with conventional irrigated systems as compared with SRI (tillering and rooting are the major varietal characteristics – both correlated with maturity -- that will determine a cultivars' potential to respond to SRI practices), and
3. Profuse root systems developed under SRI will increase the efficiency with which low concentrations of soil nutrients, derived from the mineralisation of soil organic matter and from the soil biota involved in that process (including possible contributions from mycorrhyzae and nitrogen fixing micro-organisms), can be absorbed by rice plants.

3. Materials and Methods

The initial research objective was to evaluate, through an exploratory experiment, the results obtained with SRI in Madagascar and compare it with the conventional system for (irrigated) lowland rice cultivation in West Africa (WARDA, 1999). Experiments were conducted at the WARDA farm in M'bé near Bouaké in Ivory Coast on typical lowlands and during both the dry (DS: full irrigation) and wet seasons (WS: supplementary irrigation when necessary). The climatic conditions on the M'be farm at ~300m above sea level (Table 1) are obviously very different from those in Madagascar in the Antsirabé region at elevations ranging from 1200 to 1600m. Also the soils are different: mostly of rather low fertility in Madagascar, and relatively rich lowland clay soils at the M'bé farm (40% clay; 1.0% organic carbon; C/N ratio of 12; 10 ppm available P (Olsen); CEC:15 cmol(+)/kg: Hakkeling *et al.*, 1989).

From the start it was obvious that a simple comparison between the conventional, fully irrigated and the SRI practice was hardly viable. The large number of factors involved (controllable and non-controllable: see Table 2) are such that within the scope of the present, limited research effort, it was impossible to deal with all of these as well as with the various interactions. Confounding between major production factors therefore becomes unavoidable. To minimise this problem, field experiments using factorial combinations of critical factors, were conducted over a three-year period. Moreover, two complementary types of trials were employed: *agronomic component* trials and *systems* trials (Table 3).

Following two initial *systems* experiments: a 2^3 (two varieties, two seedling/transplanting dates, two systems) in 1999 and a 4×2^2 factorial (four varieties, two plant densities, two systems) in 2000, two (non-confounded) *agronomic component* trials were conducted in 2001. The *component* trials used single replications of factorial designs to test a range of varieties with contrasting maturity cycles and their response to key SRI cultural practices. The latter were: regular nursery seed rate versus one-fifth of that rate; very early versus late transplanting; and transplanting as single plants versus clumps of three plants. In both trials the non-experimental variables were maintained as for SRI (see Table 2).

The emphasis in these trials was on the vegetative development in the nursery (recorded as plant height and plant weight) and on field plots following transplanting. For the field plots, measurements included: number of days to 50% flowering, plant height at flowering, number of tillers/hill at various intervals, and productive panicles/hill at harvest. These were recorded on the three central rows ($5m^2$ area) for an overall plot size of $12m^2$. Recordings of grain yields were, unfortunately, prevented because of labour strikes and political unrest. The results of these trials feed logically into the *systems* trials, thereby overcoming some of the internal confounding problems of the latter.

The *systems* trials also used factorial designs, but to keep the experiments of a manageable size, considerable internal confounding between variables that together make up the "package of practices/method" factor was allowed. The details for the two "packages" are summarised in Table 2. The initial *systems* trials conducted in 1999 and 2000 used randomised complete block designs with 3 or 4 replications. The 2001 trials employed a modified design by confounding the "package of practices" (conventional irrigated and SRI) with major blocks to eliminate the substantial border effects that resulted from the water seepage between adjacent plots in the earlier trials.

Associated with the major blocks are the respective agronomic management variables (irrigation regime; seedling age; transplanting technique and spacing) as presented in Table 2. Superimposed on the major blocks are factorial-treatment combinations (4 varieties x 2 plant densities/spacings: 30 x 30 and 30 x 15 cm during 2000 WS and 2001 DS, and 4 varieties x 2 seedling ages at transplanting: 10 and 20 days during 2001 WS). Each treatment combination was replicated four times within each major block in a randomised block design. This set-up permitted separate statistical analyses per major block (= "package of practices"), as well as a combined statistical analysis, comparing the two methods for a single replicate by using the higher-order interactions as an error term. Results in Tables 4 to 8 are presented as the mean values that were obtained from the calculations for the analysis of variance. Measurements were taken on 5 m^2 areas within plots of 36 m^2.

In the *systems* trials, individual plants of the four varieties were uprooted for phenological observations at the critical growth phase near 50% flowering to evaluate the effects of conventional irrigation and SRI water regimes on the general appearances and development of the respective root systems and plant (tillering) structure.

A summary of the trials conducted is presented in Table 3. All the experiments were conducted with contrasting varieties that ranged from early maturing (hybrids) to intermediate and late maturing, tall (local) cultivars.

4. Results

Data for three years of exploratory trials have been collected. First, the results of the non-confounded *agronomic component* studies will be presented, followed by those of the *systems* studies. The latter are complemented by phenological observations made on uprooted plants from the two systems.

For the sake of brevity, limited reference is made to the initial *systems* studies conducted in 1999 and 2000. These trials were crucial in gaining experience with the SRI technique and in developing the experimental designs used in 2001. The outcomes of the early trials were, however, not fundamentally different from those conducted in 2001.

4.1. Agronomic component studies

In this category, two experiments were conducted. The first trial (2001 WS) looked at seedling development in the nursery by recording seedling heights and weights over a 6-week period. Next, the impact of delayed transplanting on the subsequent vegetative development was studied. The second trial looked at the impact of transplanting density (1 or 3 seedlings/ hill) in combination with delayed transplanting (2001 DS). Both experiments used wide spacing and a reduced irrigation regime as prescribed for SRI.

The nursery measurements (height and weight of seedlings) show consistent differences over the five-week monitoring period and across six varieties in response to the "seed rate" factor (Fig. 1a and 1b). While height and weight are always superior for the low seed rate (S2), the major divergence between the two curves only occurs after the first two weeks; it is most pronounced for seedling weights. With an extended period in the nursery, the seedling development rate in the high seed rate plot is significantly retarded over that of the low seed rate. Hence, by drastically lowering the nursery seed rate, any delay in the early transplanting date (as recommended for SRI) should become less critical.

In the 2nd phase of the experiment, there was no significant impact of nursery seed rate on subsequent plant development after transplanting except for plant height; yet seedling age at transplanting (10 or 30 days) did affect significantly the number of panicles/hill (see Table 4). More importantly, the effect of a delay in transplanting (by 20 days) on the vegetative development of the plant has caused a highly significant increase by 10 days in the duration of the vegetative growth period, thereby possibly explaining the effect of a significantly increased number of panicles/hill. Similar effects were recorded earlier by Herrera and Zandstra (1980), as well as in the 2001 WS *systems* trial (see section 4.2.). While the extended vegetative growth period has led to an increased number of panicles/hill at harvest, a large proportion of the tillers present at flowering remained non-productive (see also next trial). This feature has also been reported for fully irrigated rice (Stoop, *et al.*, 2002).

Highly significant differences between varieties were recorded in seedling height and weight in the nursery as early as the third week after seeding. After transplanting, and due to the delay in transplanting, highly significant varietal effects and interactions between “varieties x seedling age (VxA)” were recorded. Varieties differed greatly in their response to a delay in transplanting and in their ability to recuperate from such a delay.

The second trial compared 9 varieties (early, intermediate and late maturing; rainfed and irrigated types) that were transplanted after 15 or 30 days as single plants or as clumps of 3 plants/hill. A single replicate of a 9 x 2 x 2 factorial was used to make a preliminary evaluation of the vegetative development features mainly in terms of tillering under SRI water management conditions.

The recorded data demonstrate differences in vegetative development between cultivars that are of great relevance to the SRI practice (Table 5):

1. There are large and highly significant differences between the 9 varieties with respect to “early tillering,” “number of panicles at harvest” and “plant height” (at flowering). Moreover, for the early transplanting treatment at 1 plant/hill, the number of tillers after 60 days ranged from only 11 and 13 for WAB 176-8-HB and IDSA 78, respectively (early maturing materials) to 54 for the late maturing variety WAB 337-B-B-13-H3.
2. Low tillering rates are associated with early maturing and short-straw varieties; high tillering rates tend to be associated mostly with full-season and tall varieties, although some of the intermediate materials also tillered profusely.
3. From the tillers present at flowering, only about half tend to produce a panicle at harvest,
4. When transplanted early (15 days old), the single seedling/hill manages to catch up with the clump of 3 plants/hill with respect to the number of tillers/hill and produce an equal number of larger panicles (see systems studies in next section).
5. When transplanting is delayed to 30 days after seeding, the plants will no longer catch up in tillering, or in plant height. The highly significant interaction “Variety x Seedling age” for height confirms that some varieties, in particular the late and some intermediate materials, are better able to compensate for delayed transplanting than are the early varieties.

The data indicate that there exist major differences between varieties in their potential to respond to an SRI type cropping system, i.e., there will be important “variety x system” interactions. Rice plants appear to have a considerable capacity through tillering and through an extension of the vegetative growth period, to compensate for a delay in transplanting. Moreover, the negative effects of delayed transplanting during the early vegetative phase (see Fig.1 and section 5.1.) will be minimised by drastically reducing the nursery seed rates.

4.2. Systems studies

The initial studies gave rather mixed results. The conventional irrigated system outyielded SRI by 48% and 21% (both HS) in respectively the 1999 and 2000 wet season (WS) trials. However, for both trials, the effects of *varieties* and of *varieties x methods* interactions were statistically significant for several major plant characteristics including grain yield. The disappointing performance of the SRI treatments was largely attributed to difficulties in properly controlling the water regime and because no nitrogen fertiliser topdressings were applied. Consequently, the 2000 WS *systems* trial was redesigned and re-run during the 2001 dry season (DS). Results are presented in Table 6, and data summaries are compared with the 2000 and 2001 WS trials in Table 8.

For the 2001 DS trial, the yield difference was reduced to 8% (NS), still in favour of the “fully irrigated” system. This progressive narrowing of the yield gap between the two methods undoubtedly resulted from the improvements made in the experimental design (permitting a better control over the water management), and from standardising the fertiliser regime.

Irrespective of these adjustments, some typical responses to SRI in terms of plant characteristics were recorded in both trials (see also photo 1):

1. SRI plants were shorter, and the tall cultivar Suakoko 8 lodged only in the “fully irrigated system.”
2. Bio-mass produced was reduced under SRI.
3. The vegetative growth cycle (up to flowering) was significantly prolonged under SRI in the 2000 WS and for some of the varieties in the 2001 DS trial (table 6).
4. The total number of panicles harvested/hill tended to be the same for SRI (1 plant/hill) as for the irrigated system (3 plants/hill).
5. In neither system did the increase in plant population have significant effects on grain yield or on other major plant and grain characteristics, except for the number of panicles/hill. Even so, the increased number of harvested panicles/hill under low density compensated almost entirely for the reduced number of panicles/hill under a plant density that was twice as high.

The highly significant “Variety x Method” interaction for grain yield, biomass and days-to-50%-flowering reflects the adaptation of some varieties, like WAB450-IBP-65-4 and WITA 12 (occasionally Bouake 189) to the fully irrigated and high plant density conditions of conventional production systems. However, the full-season, tall Suakoko 8 generally favoured the SRI conditions.

Besides the interplant competition (plant density variable), the other critical factor in realising the potential of SRI appears to be the *age of transplanted seedlings.* This factor was included in the 2001 WS trial. Moreover, the interspecific variety WAB-450-IBP-4-1 was replaced by WITA 7 because of the good early tillering ability of the latter and the unsatisfactory performance of the former under SRI conditions. Results are presented in table 7.

The 2001 WS trial confirmed the major trends signalled for the previous experiments: under SRI, plant height and biomass were reduced, while the grain yields remained the same under either system, which leads to an increased "harvest index" (see summary table 8). The variety responding most prominently in that way was the late maturing Suakoko 8. The "seedling age" factor provided important additional information: delayed transplanting had no effect in the conventional system, while under SRI the grain yield was – unexpectedly -- increased significantly.

This response is explained by the extension in the vegetative growth phase (days to 50% flowering) under SRI that was also recorded in previous experiments. In the nursery trial (section 4.1.), the date of 50% flowering was even further postponed by delayed transplanting. It was concluded that under the non-flooded SRI condition, rice plants are able to extend their vegetative growth phase, because their extensive root systems remain active for a longer period (as shown by comparing uprooted plants: section 4.3. and photos 1, 2 and 3). Moreover, seedling age (10 or 20 days old) had no significant effect on tillering in this experiment.

4.3. Phenological observations

While the exploratory scope of this research did not permit detailed measurements on root systems, a comparison between uprooted plants representing the four varieties grown under conventional irrigated and under SRI reveal distinct visual differences in both below and above ground plant development (see photos 1 and 2). Single SRI plants showed large numbers of tillers with each tiller developing its own system of adventitious roots (photo 3).

The roots from plants grown under flooded conditions were distinctly different from those under SRI: the former being predominantly brown and suberous, while the latter showed many new, still actively growing young and light-coloured (whitish) roots at flowering. Moreover, the root mass produced by a single plant grown under SRI practices exceeds that from a clump of three plants grown under the conventional, fully irrigated practice. Together with the extended vegetative growth phase recorded under SRI (section 4.2.), these features would contribute to the substantially increased panicle sizes and grain sizes of SRI plants as reported initially from Madagascar (Uphoff and Randriamiharisoa, 2002).

5. Discussion

This article attempts to give an initial justification and explanation of SRI practices. The reported results raise a number of fundamental questions, as will be discussed next on the basis of hypotheses defined in section 2. From this discussion follow certain implications for future research and for the possible practical potentials of SRI for resource-poor farmers.

5.1. Review of results against the initial hypotheses

The WARDA field experiments have combined some of the factors judged crucial in achieving the extraordinary rice grain yields reported for SRI in Madagascar and elsewhere. Admittedly, the critical factor of soils, their organic matter characteristics and use of organic sources of fertilisers could not be investigated within the limited scope of this research.

While grain yields of the experiments fell far short of those reported from Madagascar and elsewhere, certain critical responses were confirmed across different experiments conducted in different seasons and over a three-year period. These results underscored some of the key plant features and crop responses that might be at the basis of potentially very high SRI yields.

5.1.1. Hypothesis 1: Very early transplanting as a determinant of crop development

The initial work by Laulanié (1993) in Madagascar, but also the subsequent efforts to test and to disseminate SRI in Asia and elsewhere have all emphasised the requirement of careful and early transplanting of very young, 8 to 15 days old, seedlings. Theoretically the reasons for this practice are plausible, but to farmers it presents serious practical bottlenecks. These apply to the need for an increasingly precise timing of field operations, the related labour constraints, and the increased risks involved in using very small and vulnerable plants (due to unpredictable floods, weeds, pests, etc.).

Neither the two *agronomic component*, or the 2001 WS *systems* studies have confirmed this requirement for very early transplanting. Therefore, based on these data "hypothesis 1" (see section 2) might be rejected, except for the fact that trials in Madagascar and in several South and South-eastern Asian countries have recorded the opposite, namely SRI rice plants that matured 7-15 days sooner.

The results of the present trials suggest that the rice plant has important compensation capabilities (such as tillering and delayed flowering) that can be enhanced further by cultural practices (reduced seed rates in the nursery, varietal choice, adjusted spacings of transplants, etc.). Consequently there might well be several other and more practical ways to handle the early development phase instead of the currently emphasised very early (8 to 15 days) transplanting. In particular the use of greatly reduced (e.g. one-fifth or even one-tenth) seed rates in the nursery may be an attractive alternative. Next, single seedlings of approximately 20 days old (rather than 4 to 6 weeks old as used by many risk-adverse, resource-poor farmers) could be transplanted conveniently using a wide (e.g. 30x30 cm) spacing.

These are important practical results for farmers. While saving them considerably on seed requirements, this also permits them to cope with unpredictable, early season rainfed conditions that interfere seriously with the optimum planning and precise timing of transplanting. Moreover, the greatly reduced number of seedlings required for SRI provides smallholders with alternatives like growing seedlings in trays and/or use several seeding dates while awaiting adequate rainfall for transplanting. Moreover, the absence of negative responses from delayed transplanting on plant development (biomass and tillering) and grain yield may indicate that *widely spaced, single transplants* and *non-flooded conditions* are more critical components of the SRI technology, than are *very young transplants*. While this issue requires still further study, if true, it has two important practical ramifications: flexibility at transplanting is increased, and weed control during the early vegetative phase is greatly facilitated. However, the results also indicate that varieties differed greatly in their response to SRI depending on their respective maturity cycle and tillering habit (see next section).

5.1.2. Hypothesis 2: Plant characteristics of SRI adapted varieties; G x E interactions

Rice is being grown under very diverse agro-ecological conditions and production systems that range from rainfed uplands and lowlands with or without irrigation and/or drainage facilities to river floodplains with floating rice and entirely non-controlled water regimes. It follows that within the *Oryza* specie there is an enormous genetic diversity that could be exploited in rice cultivation. Therefore, the significant "variety x methods" interactions recorded in the various studies are not surprising and lead to several preliminary conclusions about the desirable plant characteristics for SRI-adapted varieties.

First, adapted varieties must have large tillering abilities to exploit the available "space" effectively. Second, as noted also by de Datta (1981), this tillering will be associated mostly with materials of intermediate and/or full-season maturity. While all rice varieties responded to SRI practices in terms of increased tillering per plant, very early maturing varieties (like the WAB450-IBP65-4) will simply lack "time" to fully exploit this feature. Most early and intermediate, short-statured varieties -- a major output of many ongoing breeding programs -- have been selected specifically for intensified rainfed and/or irrigated systems. WITA 12, for instance, develops a dense bunch of erect tillers, whereas varieties like Suakoko 8 and to a lesser extent Bouake 189 showed an unfurled bunch of tillers for each individual plant (see photo 1). Third, the SRI plants developed profuse root systems, since each new tiller generated adventitious roots to support it. Consequently, the total soil volume tapped by each individual plant is greatly increased with potentially very important implications (see next section). Obviously, this feature will be most prominent for varieties with longer maturity cycles, thereby contributing to an increased relevance of *genotype x environment* (G x E) interactions under SRI conditions (see results of the agronomic component trials).

Hypothesis 3: Profuse root systems as a determinant of increased resource use efficiency

The WARDA experiments recorded reductions in biomass production and in plant height under SRI, while grain yields were unchanged (fertiliser levels being the same), leading to an increased "harvest index." Simultaneously, the vegetative growth phase was extended under SRI water management conditions, indicating that conventionally grown, irrigated rice halts its development pre-maturely. This conclusion is supported by observations on the respective root systems and explains why under SRI the total number of panicles, their individual sizes (number of grains/panicle and individual grain size) and consequently total grain yield are potentially increased (Uphoff, *et al.*, 2002; Stoop, 2003). The overall effect of the SRI practices, therefore, points to an increased efficiency in resource use, particularly for water and plant nutrients.

The profuse root systems, observed under SRI, constitute a key feature for plant nutrient management, uptake and utilisation, and plant development. Extensive root systems per individual plant automatically raise the significance of soil microbiological processes – including mycorrhizae and biological forms of nitrogen fixation – in meeting the plants' nutrient requirements. An extensive root system is also more likely to profit from a greater synchronisation between rice N demand and the N released from organic residues (Toomsan, *et al.,* 2000) than is possible with mineral N topdressings. By comparison, the limited root systems of fully irrigated rice that are associated with anaerobic soil conditions and high plant densities will be less effective in nutrient uptake including the nitrogen from topdressings.

The wide spacing between plants under SRI leads to a prolonged, open crop canopy. Many scientists object to this feature because it diminishes the initial rate of radiation utilisation by the crop as compared with the conventional practices. Chinese research (Longxing *et al.*; 2002; but also research in Japan as cited by Horie *et al.*, 2005) suggests that this might be compensated for by continued photosynthetic activity in the older leaves, since these are not shaded out. Moreover, the Chinese scientists recorded in the same trial more profuse and deeper root systems. These two features that resulted from the use of single, widely spaced plants will greatly affect competition, both above-ground for radiation and below-ground for plant nutrients (and for moisture in rainfed systems). SRI and other low external input technologies relying mostly on organic forms of fertilisers, therefore, may require rather different perspectives on the dynamics of soil fertility and plant nutrition, as well as the plant physiological processes involved.

5.2. Implications for future research

Basic research aimed at establishing a viable comparison between two fundamentally different production systems (made up of several interdependent variables) presents considerable scientific/methodological challenges. These involve the choice of crucial experimental variables and a critical concern about setting the non-experimental variables at realistic levels. Complicating aspects are comparisons between different soil types and the effects of *past land use* in each individual location. The regular use of agricultural chemicals on fields of agricultural experiment stations or on many commercial farms constitutes an undervalued constraint. Its significance is underscored by the time required – a minimum of four years – to rehabilitate soils when switching from a conventional to a biological form of agriculture (Bulluck *et al.*, 2004). It follows that this may have critically affected the outcome of the WARDA SRI experiments, but also those by IRRI (Sheehy, *et al.*, 2004). Moreover, varieties must be included as a variable in any field experiment aimed at comparing two different systems (it being highly unlikely that a single variety will be equally adapted to either system). The Sheehy *et al*. (2004) research conducted in China has ignored these aspects, thereby arriving at poorly founded conclusions (Stoop and Kassam, 2005).

The results reported in this article indicate that SRI type practices may offer significant scope for increasing the efficiency of resource use (water, nutrients and seeds; and perhaps eventually also land and labour). There remain, however, many inter-linked research questions that originate mainly from the fundamentally different soil conditions created under SRI. These will be the combined effects of soil drainage during the vegetative development phase of the crop and the use of organic types of fertilisers. Even so, the high rice yields obtained by some small farmers using SRI type practices in Madagascar and elsewhere raise intriguing questions about sustainable soil fertility management and theoretically derived yield ceilings for rice. These questions cannot be resolved through the conventional soil physical and chemical concepts, and the crop growth models developed for inundated soils.

High SRI yields seem to be in conflict with chemically available soil nutrients and nutrient budget concepts (Smaling, 1998; Smaling, *et al.*, 1997), as well as with plant physiological theories (Horie *et al*., 2005). Integrated soil fertility management approaches that combine mineral and organic fertilisers (Sanchez and Jama, 2000) do not provide the required fundamental insights either. Therefore, it is postulated that the soil water regime in combination with organic fertilisers – as under SRI – cause fundamental changes in the soil environment and with it a considerable increase in the significance of soil biological processes.

Organic matter quantity and quality (C/N ratios), soil pH, soil aeration and soil humidity are likely to be critical factors in those processes (Palm *et al.*, 1997). A related soil biological effect – with potentially large impacts, including the outcome of field experiments – will be the presence of various toxic agents. These could be polyphenol decomposition products liberated during mineralisation, but also occasionally soil pollution with heavy metals (see also Palm *et al.*, 2001). These products can cause instantaneous effects on crop growth, but may also act more subtle on soil micro-organisms (e.g., Rhizobia) without immediate visual impacts (Giller *et al.*, 1998).

Moreover, under farm conditions there will often be large location- and farmer-specific variations as reflected in differences between land types (e.g., uplands and lowlands) and between types of manures (compost, green manure, animal manure, crop residues, household refuse, etc. and their various combinations). These will cause large variations in crop responses (Vityakon *et al.,* 2000) that may be difficult to explain scientifically in the absence adequate soil biological parameters.

Agricultural intensification requires that farmers maximise their returns from various investments (e.g., in labour, in organic and/or mineral fertilisers, etc.). Suitably adapted varieties, precise timing of cultural practices (see also Giller, 2002) and increased efficiency of resource/input use are essential pre-conditions. Ladha, *et al.* (1998) provide a useful illustration of the implications of varietal choice: early-maturing rice varieties achieved maximum grain yields at about 200 kg N/ha, while for intermediate and late-maturing types this rate decreased to 150 and 100 kg N/ha, respectively. The present field trials recorded a comparable feature: the intermediate and late-maturing varieties were generally more responsive to SRI than the early materials because of the increased tillering and rooting of the former. The preceding considerations are potentially of great practical significance in view of the large proportions (up to 70%) of applied fertiliser nitrogen that are being lost commonly in rice production systems in Africa (Wopereis *et al.*, 1999) and in Asia (Ladha *et al.*, 1998). For smallholders to achieve effective intensification (i.e., increased production and productivity while minimising losses to the environment) will still require a far better appreciation of the intricate processes that occur in the interface between crop and natural environment.

5.3. Practical implications for adaptation to diverse agro-ecological rice systems

The SRI practices as initially developed and described by Laulanié (1993) are extremely delicate like the transplanting of very young, 10-day old, seedlings, and very sensitive to timely implementation and planning (for transplanting, as well as for the management of irrigation water, land levelling and weeding). Therefore, scientists have often objected that SRI constitutes more of a *small-scale horticultural* than of a modern, *large-scale agricultural* operation.

Madagascar farmers, however, practise SRI successfully during the warm rainy season without having much control over water. Their strategy is to minimise the risks of flooding during the crops' vegetative stage by seeding / transplanting early in the rainy season, while promoting rapid drainage in case of abundant rainfall. Informal field interviews (Stoop, 2003) also revealed that SRI was practised by a limited group of farmers -- the most professional and keenly interested individuals -- and then on fields that are located rather closely to their homes. On their more distant bush-fields, these individuals continue to use mostly traditional, extensive practices. This implies a situation of *partial adoption*, (something rather different from the disadoption reported by Moser and Barrett, 2003) and an entirely logical response given the large environmental and social diversity.

The diversity of rice growing environments – certainly under rainfed conditions – as encountered in West Africa, Madagascar and Asia, is huge. With it the location-specific problems – whether they involve water, soil fertility management, or outbreaks of pests and diseases -- will always be diverse. Fortunately, the genetic variation in rice (in particular for the local landraces) is also huge, thereby offering numerous possibilities to adapt SRI to local bio-physical and socio-economic conditions, first by exploiting the G x E interaction (Richards, 1985). A consequence is, however, that considerable "farmer-led experimentation" will be required in order for them to gain experience and to adapt the SRI practice to their local conditions. Such informal experimentation will eventually permit farmers to economise on labour and to reduce risks.

The WARDA experimental results have underscored that adjustments in agronomic management are a major way to cope with location-specific field variations and constraints. Regular field observation, thereby permitting timely implementation of field operations (weeding, drainage, etc.) and the use of SRI adapted varieties, mainly of intermediate and late-maturing types, will be important. Such varieties inherently cope more effectively with non-ideal growing conditions and agronomic practices that are common for diverse production systems and practices of resource-poor farmers, than would the modern high-yielding and early-maturing materials. Moreover, the latter tend to have maturity cycles that are either too short or have canopy structures that are inappropriate for effectively responding to SRI cultural practices (see photo 1), thereby automatically leading to increases in labour and risk levels. By comparison, the later-maturing varieties contribute to systems that will be more robust and more effective in coping with the diverse and non-ideal conditions encountered in smallholder fields.

6. Concluding comments

SRI is surrounded by much controversy and its principles, as well as its practical significance for farmers are frequently doubted (Sheehy *et al.*, 2004). Common criticisms are that it is not backed up by solid agronomic research data (Dobermann, 2003), and that its successful introduction would require continued large-scale -- and therefore very costly -- extension and training efforts (Moser and Barrett, 2003). These criticisms are valid only to a limited extent. Rather it underscores the considerable knowledge gaps that still exist even for a crop like rice, as well as the frequently unrealistic and very costly objectives (like the routine dissemination of standardised production technologies) pursued by many rural development projects.

A most striking outcome of the present trials has been that agronomic management – for water in particular -- had fundamental impacts on rice plant characteristics such as plant height, maturity, and total biomass production, but also on key features like grain and panicle size. These results point to an increased efficiency in water use as well as in nutrient use under SRI type management. Normally such improvements in plant features have been the prerogative of plant breeders. The present results suggest, however, that rapid and substantial improvements in production systems can be achieved through relatively simple adjustments in various field management practices (see also Horie *et al.*, 2005). By comparison, the on-going breeding and selection efforts for N-use efficiency (Ladha *et al.*; 1998) and for certain, presumably superior plant types (the new rice plant: Holmes, 1994) are unlikely to resolve major concerns like losses in biodiversity and environmental pollution that are associated with modern agriculture.

From an agricultural development perspective, the field reconnaissance study conducted in Madagascar (Stoop, 2003) confirms that while SRI has been characterised as a *low external input technology*, it is quite “knowledge-intensive.” A widespread adoption of SRI type practices (but also other low external input technologies), therefore, is generally constrained by inadequate theoretical knowledge and field research, which does not permit a proper assessment of the complex trade-offs (also in economic terms) involved in comparisons between two fundamentally different production systems.

Starting from a holistic/integrated perspective, the options for future research indicated in this paper may contribute to novel, more resource-use efficient and environment-friendly production systems for rice as well as for other crops. Though the reported research admittedly had a limited scope, the results raise some fundamental questions as to how agricultural intensification might be achieved most effectively given the diverse resource constraints as faced by large commercial farms as well as by smallholders: the main target group for the fight against poverty. Both groups, as well as society in general, stand to gain from comprehensive and diverse research efforts.

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Table 1: Climatic data for average monthly rainfall and 75% probability, and mean monthly temperatures (30 year averages) as recorded for Bouaké.

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Rainf. (av.)	11	47	86	126	134	156	118	98	183	139	32	16	1146
Rainf.(75% prob)	0	11	63	105	105	90	48	57	118	82	9	0	
Av. Temp.(C.)	26.2	27.3	26.9	26.5	25.8	24.4	23.5	23.3	23.7	24.3	24.9	25.1	

Table 2: Comparison between the major agronomic components of SRI and conventional irrigated rice technology as practised in the WARDA trials.

Production system	Age of seedlings	Transplants/ hill	Spacing of hills	Transplants per m^2	Water management	Fertility management (kg/ha)	Weed management
Conventional	20-30 days	3	30x15 cm;	80 to 100	Continuous flooding	40N40P40K basal+ 50Ntop	2 rounds
SRI	8-15 days	1	30x30 cm	11	Moist soil; intermittent drying	Same	3 to 4 rounds

Table 3: Summary of experiments conducted from 1999 till 2001 on lowlands at WARDA during wet (WS) and dry (DS) seasons.

Year	Season	Type of trial	Factorial variables and number of levels	Nb of Reps	Results
1999	WS	Systems	Methods (2) x Varieties (2) x Seeding dates (2)	4	-
2000	WS	Systems	Methods (2) x Varieties (4) x Plant densities (2)	3	Table 8
2001	DS	Component	Varieties (9) x Plant densities (2) x Seedling ages (2)	1	Table 5
2001	WS	Component	Varieties (6) x Nursery seed rate (2) x Seedling ages (2)	1	Table 4
2001	DS	Systems	Methods (2) x Varieties (4) x Plant densities (2) (modified design)	1 (4)	Tables 6 and 8
2001	WS	Systems	Methods (2) x Varieties (4) x Seedling ages (2) (modified design)	1 (4)	Tables 7 and 8

Table 4: Agronomic component trial (2001 WS): impact of nursery management (seed rate) on the subsequent plant development following early (10 days) and late (30 days) transplanting for six varieties.

Treatments	**Plant characteristics**			
	Tillers/hill at flowering	**Panicles/hill at harvest**	**Plant height (cm)**	**Nb of Days to 50% flowering**
Varieties (V)	NS	**	**	**
WAB 450-IBP-65-4	17.4	7.6	109	98
Bouake 189	22.8	14.0	106	115
WITA 12	19.5	12.6	110	118
Suakoko 8	26.3	15.8	145	143
WITA 7	23.8	11.9	104	109
IR 22-107-19-2-1	19.4	14.4	111	116
Nursery seed rate (S)	NS	NS	*	NS
20 g/m	22.7	12.5	111	116
4 g/m	20.4	13.0	117	116
Seedling age at transplanting (A)	NS	*	NS	**
10 days	23.2	11.9	115	111
30 days	19.9	13.7	113	121
Interactions	NS	VxA**	VxA**	VxA**
C.V.(%)	20.1	12.3	4.8	3.4

*: Significance at 5% level, **: Significance at 1% level, NS: Non-significant; CV: coefficient of variation.

Table 5: Agronomic component trial (2001 DS): impact of transplanting density / method (clumps versus single plants) and of seedling age at transplanting (15 and 30 days) on plant development for nine varieties representing different maturity types.

Treatments	**Plant characteristics**			
	Maturity type	**Tillers/hill at 45 days**	**Panicles/hill at harvest**	**Plant height (cm)**
Varieties (V)		**	**	**
WITA7	Intermediate	20.6	19.8	99
WAB 326-B-B-2-H5	Early	14.0	12.4	110
WAB 176-8-HB	Early	8.0	11.7	97
IDSA 78	Early	10.6	14.0	85
WITA 12	Intermediate	23.0	26.8	131
IDSA 6	Early	11.6	13.7	96
WAB 337-B-B-13-H3	Late	20.2	19.7	128
FARO 8	Late	25.8	16.7	144
IR 22-107-19-2-1	Intermediate	20.9	22.5	115
Transplanting density (D)		**	**	NS
3 pl/hill		19.7	18.9	112
1 pl/hill		14.6	16.0	111
Seedling age at transplanting (A)		**	**	**
15 days		21.6	20.0	117
30 days		12.7	14.9	107
Interactions		NS	NS	VxD**
CV (%)		16.6	14.0	1.8

*: Significance at 5% level, **: Significance at 1% level, NS: Non-significant, CV: coefficient of variation.

Table 6: Systems trial (2001 DS): summary of results comparing the conventional irrigated system with SRI for four varieties planted at two spacings.

Treatments	**Crop/plant characteristics**									
	Grain yield (t/ha)		**Nb of days to 50% flowering**		**Plant height (cm)**		**Panicles/hill[1]**		**Biomass (t/ha)**	
Method/systems (M)	NS		NS		**		NS		**	
Irrigated	4.0		114		121		11.4		12.1	
SRI	3.7		115		111		11.3		9.3	
	Irrigated	**SRI**	**Irrigated**	**SRI**	**Irrigated**	**SRI**	**Irrigated**	**SRI**	**Irrigated**	**SRI**
Varieties (V)	**	**	**	**	**	**	**	**	*	**
WAB 450-IBP-65-4	3.6	2.6	108	104	110	99	7.4	7.2	6.7	4.4
Bouake 189	6.1	4.1	113	115	111	101	11.0	13.2	15.3	10.7
WITA 12	3.6	4.0	111	114	122	116	11.8	11.2	15.8	11.7
Suakoko 8	2.8	4.1	124	128	141	128	15.2	13.6	10.5	10.4
Hill spacing (S)	NS	NS	NS	NS	NS	NS	**	**	NS	NS
30 x 30 cm	4.0	3.7	114	116	120	111	14.7	14.4	11.8	9.5
30 x 15 cm	4.0	3.7	113	115	121	110	8.0	8.2	12.4	9.2
Interactions										
V x S	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
V x M	**		**		*		*		**	
M x S	NS		NS		NS		NS		NS	
C.V. (%) method blocks	24.3	21.4	4.0	1.8	7.1	3.9	19.3	18.3	23.1	16.9
C.V. (%) Combined analysis	23.0		3.1		5.9		18.8		21.2	

*: Significance at 5% level, **: Significance at 1% level, NS: Non-significant, CV: coefficient of variation.

[1]: Panicles originating from 3 pl/hill for irrigated and from 1 pl/hill for SRI practices.

Table 7: Systems trial (2001 WS): summary of results comparing the conventional irrigated system with SRI for four varieties using two seedling ages at transplanting.

Treatments	**Crop/plant characteristics**									
	Grain yield (t/ha)		**Nb of days to 50% flowering**		**Plant height (cm)**		**Panicles/hill**[1]		**Biomass (t/ha)**	
Method/systems (M)	NS		**		**		**		NS	
Irrigated	4.0		98		108		10.9		6.8	
SRI	3.9		105		97		15.2		5.6	
	Irrigated	**SRI**	**Irrigated**	**SRI**	**Irrigated**	**SRI**	**Irrigated**	**SRI**	**Irrigated**	**SRI**
Varieties (V)	*	*	**	**	**	**	**	**	**	**
WITA 7	4.5	4.0	90	97	91	76	9.9	14.3	5.8	5.4
Bouake 189	3.3	3.8	92	98	93	85	11.5	14.0	4.7	4.4
WITA 12	3.8	3.4	96	104	104	92	12.0	17.3	4.8	4.9
Suakoko 8	4.4	4.3	114	121	143	134	10.1	15.2	12.1	7.9
Seedling age (A)	NS	*	**	**	NS	NS	NS	NS	NS	NS
10 days	4.0	3.6	95	102	108	97	10.9	14.9	6.9	5.6
20 days	4.0	4.1	101	108	108	97	10.8	15.5	6.7	5.7
Interactions										
V x A	NS	NS	**	**	NS	NS	NS	NS	NS	NS
V x M	NS		NS		**		*		**	
M x A	NS		NS		NS		NS		NS	
C.V. (%) method blocks	22.1	14.0	1.7	3.0	1.8	2.3	11.2	11.5	19.6	29.1
C.V. (%) Combined analysis	18.6		2.4		2.3		11.5		22.5	

*: Significance at 5% level, **: Significance at 1% level, NS: Non-significant, CV: coefficient of variation.

[1]: Panicles originating from 3 pl/hill for irrigated and from 1 pl/hill for SRI practices.

Table 8: Systems trials: comparisons of major results obtained over three seasons of field experimentation.

	WS 2000			**DS 2001**			**WS 2001**		
Grain yields (t/ha)	**Irrigated**	**SRI**[1]		**Irrigated**	**SRI**		**Irrigated**	**SRI**	
Varieties:	**	**		**	**		*	*	
WITA 7	-	-		-	-		4.5	4.0	
WAB 450-1BP65-4	3.5	2.9		3.6	2.6		-	-	
Bouaké 189	5.2	4.6		6.1	4.1		3.3	3.8	
WITA12	5.2	3.5		3.6	4.0		3.8	3.4	
Suakoko 8	3.8	3.7		2.8	4.1		4.4	4.3	
Crop/plant characteristics									
Grain yield (t/ha)	4.4	3.7	**	4.0	3.7	NS	4.0	3.9	NS
Bio mass (t/ha)	8.5	7.1	**	12.1	9.3	**	6.8	5.6	NS
Nb. of days to 50% flowering	84	90	**	114	115	NS	98	105	**
Plant height (cm)	122	115	**	121	111	**	108	97	**
Panicles/hill[2]	14.4	11.7	**	11.4	11.5	NS	10.9	15.2	**
1000 grain weight (g)	25.5	25.1	*	25.2	27.2	**	26.4	25.6	NS
Harvest Index	0.52	0.52	-	0.33	0.39	-	0.59	0.70	-

*: Significant at 5% level, **: Significant at 1% level, NS: Non-significant.

1) SRI in WS 2000 did not receive N top-dressings.

2) Panicles originating from 3 pl/hill for irrigated and from 1 pl/hill for SRI practices.

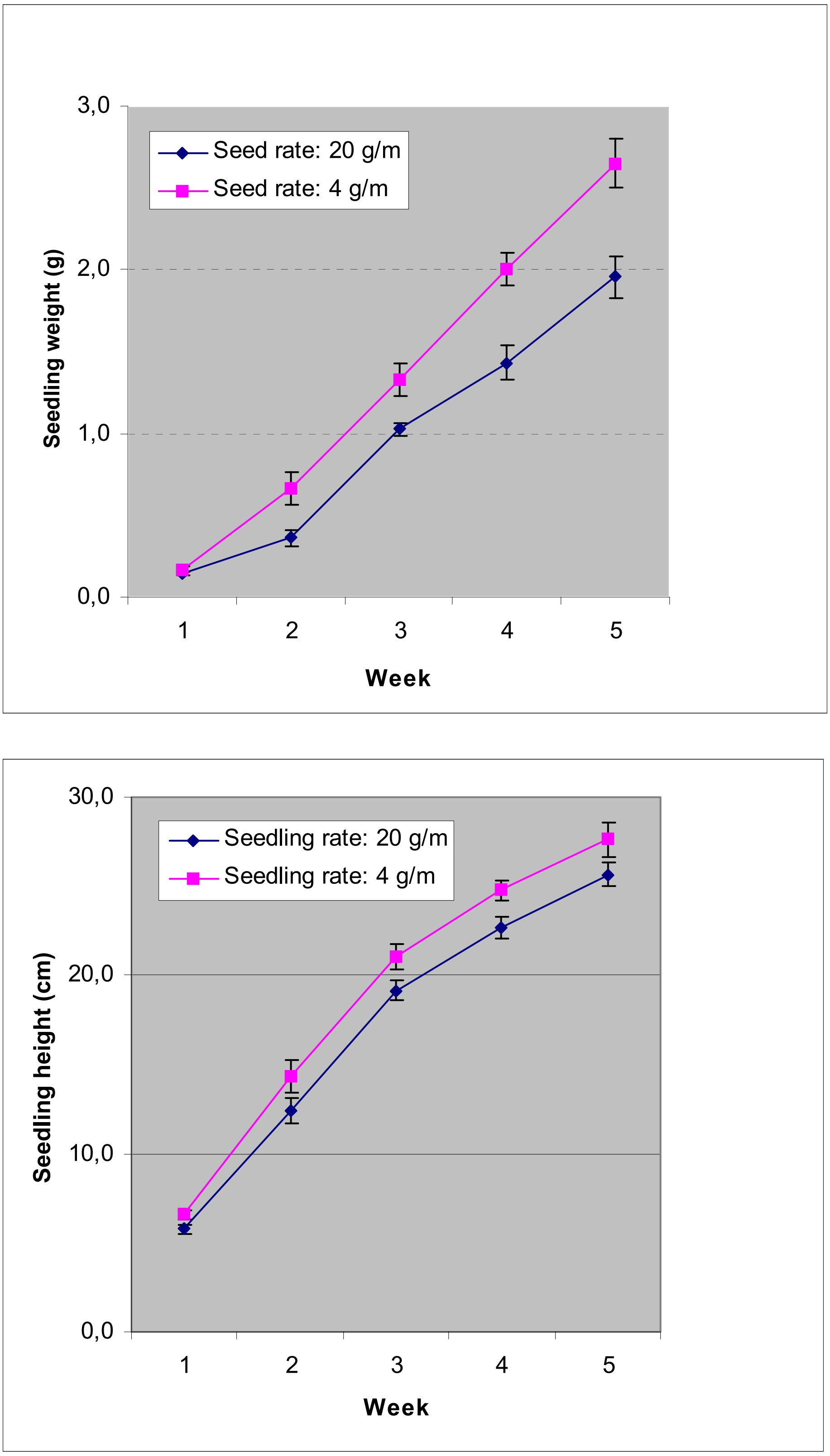

Figure 1: Seedling development in the nursery over a five-week period in response to the regular high seed rate and one-fifth of that rate: a) total seedling weight (g) for samples of 25 plants; b) average seedling height (cm)

Photo 1: Responses of 4 rice varieties to fully irrigated (on the left: 4 clumps of 3 transplants/hill) and to SRI (on the right: 4 plants as single transplants/hill) grown in the 2001 DS systems trial. The two varieties at the extreme left and right represent improved (early) cultivars selected for fully irrigated intensified systems; the two varieties in the center represent a full-season, tall, local (Suakoko 8) and an intermediate (Bouaké 189) cultivar. Note the extensive tillering and root development of the two latter varieties under the SRI conditions.

Photo 2: On the left SRI plant derived from 1 seedling/hill; on the right fully irrigated clump of 3 seedlings/hill. Note increased tillering and continuing root development (newly formed whitish roots) for the SRI plant, as compared with the brownish, suberised roots from the fully irrigated clump

Photo 3: Rootsystem of a single SRI plant; note the continuous development of new adventitious roots at the base of each tiller.