Water-saving rice production systems. Proceedings of an international workshop on water-saving rice production systems at Nanjing University, China, April 2-4, 2001

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Plant Research International B.V., Wageningen
July 2001

Report 33

WAGENINGEN UR

This publication is sponsored by the Partners in Water for Food programme. The Government of the Netherlands initiated the Partners in Water for Food programme in the backdrop of the Second World Water Forum, held in 2000 in The Hague. At that meeting seven challenges were identified, founded on the overriding and generally accepted concept of Integrated Water Resources Management. Partners in Water for Food is focussed on the challenge of securing the world's food supply, particularly of the poor and vulnerable, in a situation of increasing demands for water. It responds to this challenge through a programme of capacity building, knowledge exchange and cooperation between partners in different countries. In line with Integrated Water Resources Management, the programme emphasizes the need for comprehensive solutions in managing water demand for the production of food. The programme operates under the theme 'Capacity Building for Agricultural Water Demand Management'.

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Summary

The first and second World Water Conference in Marrakech and The Hague, respectively, have catalysed much political and scientific debate on the use of water to meet the growing needs of the global human population and of natural ecosystems. At the second conference in March 2000, various vision documents were presented which are currently being implemented. This report describes the result of an action project in the field of water for food and rural development program that is implemented and financed by the Dutch Ministry of Agriculture, Nature Management and Fisheries. The overall goal of the project is to design and demonstrate successful, high-yielding lowland rice production systems with low water input in five major rice granaries in China, India, Indonesia and Madagascar, and to analyze their impact on farm-households and on the regional hydrology in the selected areas.

An inception workshop on this project was held at Nanjing Agricultural University, China from 2 to 4 April, 2001 of which this report presents the proceedings. The objectives of the meeting were:

- To discuss the state of the art with respect to water-saving rice production systems and to exchange knowledge about such systems.
- To exchange knowledge about tools enabling the analysis of the impact of water-saving rice production systems at various scale levels (field, farm and region).
- To identify feasible research goals.
- To define a research program for the year 2001 and beyond that contributes to the realization of these goals.

Various participants of the workshop (e.g. China, India, Indonesia and Madagascar) showed that it is possible to achieve rice yields with water-saving techniques equivalent to or higher show yields from conventional flooding systems. However, no systematic research has been done to understand the performance of water-saving rice systems, to examine overall resource use, to estimate the overall water-saving and to stimulate adoption of such systems.

To enable a more systematic approach to design and demonstrate successful water-saving rice production systems three project goals were identified: (i) evaluate whether water, land and labor productivity can be increased simultaneously in water-saving rice production systems, (ii) demonstrate the benefits of such systems for resource-poor farmers, and (iii) quantify the potential regional water savings and reallocation options compared to other options.

Nine research topics were identified that should get priority in future research on water-saving rice production systems. These research priorities range from field to regional scale and contribute differently to realization of the project goals: (1) weeding/aeration, (2) biological nitrogen fixation, (3) transplanting, (4) crop establishment, (5) cultivars, (6) nutrient management, (7) regional hydrology, (8) farmers welfare, and (9) water quality. The participants from China, India, Indonesia and Madagascar defined research programs related to their ongoing research agendas, location-specific interests and expertise. In these countries various research and demonstration experiments will be carried out, each including one or more of the identified research priorities.

The project generates three important outputs: (i) consolidation of current and generation of new knowledge on water-saving rice production systems that enables to identify the potentials of such systems for different agro-ecological and socio-economic conditions; (ii) capacity building and exchange of knowledge, both between North-South and South-South. Since MSc and PhD students participate in the project, young scientists from developing countries are trained in analysis and integration of knowledge with respect to rice production systems; (iii) new information on water-saving rice production systems that increases awareness among various stakeholders (from farmers to local policy makers) and contributes to the international debate on water for food.

1. Introduction

Over the past years, the first and second World Water Conference in Marrakech and The Hague, respectively, have catalysed much political and scientific debate on the use of water to meet the growing needs of the global human population and of natural ecosystems. At the second World Water Conference in March 2000, The Hague, the Dutch government pledged to increase its support of water sector activities in developing countries to contribute to the security of the world's water supply in the 21st century. One of the support initiatives is implemented and financed by the Dutch Ministery of Agriculture, Nature management and Fisheries in the programme 'Partners in Water for Food' that deals with water for food and rural development issues. This report describes the results of an inception workshop on water-saving rice systems that was carried out within this framework and funded by the program 'Partners in Water for Food'.

The project 'Water-saving Rice Systems' explores novel ways of rice production that may have dramatic impact on agricultural water consumption. It addresses key issues at a range of scales by incorporating methodologies that enable the integral assessment of the promise and impact of water-saving rice production systems.

The overall goal of the project is to design and demonstrate successful, high yielding lowland rice production systems with low water input in five major rice granaries in China, India, Indonesia and Madagascar, and to analyze their impact on farm-households and on the regional hydrology in the selected areas.

To meet this goal, the following direct objectives must be achieved:
1. Assessment of the impact of reduced water input on rice yield and water consumption at field level, through dedicated field and pot experiments.
2. Assessment of the bio-physical and socio-economic consequences of the altered system at the farm and farm-household level.
3. Quantification of the regional hydrology for selected watersheds, to illustrate the regional consequences, for example, for urban and industrial water use.
4. Strengthening the international rice networks via exchange of information and education programs.

An inception workshop on this project was held at Nanjing Agricultural University, China from 2 to 4 April, 2001. The objectives of the meeting were:
- To discuss the state of the art with respect to water-saving rice production systems and to exchange knowledge about such systems.
- To exchange knowledge about tools enabling the analysis of the impact of water-saving rice production systems at various scale levels (field, farm and region).
- To identify feasible research goals.
- To define a research program for the year 2001 and beyond which contributes to the realization of these goals.

This report is a compilation of the papers that were presented during this workshop and it gives a concise description of the workshop results. Chapter 2 describes the necessity for changing inundated rice production systems. In addition to the reducing availability of water, the limited labor and land availability should be addressed. As a premium, non-inundated cultivation may reduce emission of the greenhouse gas methane.

Chapter 3 describes the need for water-saving management and expected agronomic difficulties in India. The result of a small curiosity-driven experiment in the State of Tamil Nadu is already changing opinions on inundated rice cultivation.

Indonesia (Chapter 4) encounters comparable problems as India with decreasing rice productivity and a degrading natural resource base. Promising results have been found with water-saving management practices.

In Madagascar (Chapter 5), limited access of resource-poor farmers to external inputs, such as fertilizers and bio-chemicals triggered the search for management practices in rice cultivation without chemical inputs. This resulted in the so-called 'System of Rice Intensification (SRI)' with fields that are kept non-flooded for almost the entire crop cycle, with application of large amounts of organic manure, along with frequent weeding and transplanting of very young seedlings. Yields of 2 t ha^{-1} under common practices increased to over 6 t ha^{-1} under this system in experimental fields, while even higher yields are being reported from farmers' fields.

Water shortage and food production increase are major driving factors in agricultural development in China (Chapter 6). Various management practices are being examined to increase rice yield, while reducing water use. In the province Jiangxi, research is focussed on raising seedlings to facilitate transplanting and to reduce transplanting shocks in fields with less water use.

More in-depth physiological analysis on the effects of water stress in rice is done at the Nanjing Agricultural University in Jiangxu province, China (Chapter 7). Derived water stress threshold values can be used to guide water management when properly translated from pot and field experiments to observations that can be easily done by farmers in their fields.

Reduced water use at the field and farm level may provide new opportunities for water use in other regions or sectors, but water saved in one area may not be directly available for use in another area. In Chapter 8, two tools are described to explore the consequences of water-saving at the field and farm level for production at the watershed or the irrigation scheme. One tool allows quantifying the consequences of changing water management practices at the field level for an irrigation scheme, while the other tool allows exploring the consequences of changing future water demand for the level of a watershed.

In adopting new management practices, farmers will consider opportunity costs of using or freeing resources (Chapter 9). Thereby, farmers' rate of adoption and adaptation of new technology depends on farmers' behavior and external factors. Adoption of win-win options, e.g. increase of land and labor productivity, may need less policy support than win-lose options. In designing water-saving management practices for rice, such aspects must be taken into account, creating true interactive technology development between technical and socio-economic sciences.

Priority research topics that were identified by the participants of the workshop have been summarized in chapter 10. Agreements on experiments and other follow-up activities have also been recorded. These have been attached in annexes.

The importance of this research area is considered to be so high that all participants agreed to actively pursue for additional funds and to place the topic high on the research agenda of the international discussions on water for food.

2. Water for food: Converting inundated rice into dry rice

P.S. Bindraban (Plant Research International, Wageningen, the Netherlands)

Abstract

Over the past years, much public and political attention has been given to current and future water-related problems. Concerning agriculture, the international debate centers around efficient use of water in irrigation systems and on the competition of food and nature for water. The vast challenges ahead concerning water and food necessitate to explore all means, also outside this 'water sector'. The potential to increase food production in rain-fed agricultural systems is huge, as are potential savings of water in inundated rice production systems. This paper gives a concise description of the arguments that urge the need to seriously investigate the conversion of inundated rice cultivation into cultivation practices that use substantially less water. In addition to water saving, other relevant factors and developments are reviewed that govern such transition. Labor scarcity is already pushing transplanting into direct seeding practices, while increasing production pressure on land is stimulating multiple cropping. In addition, human-induced climate change feeds international debates on emission reductions, such as methane from inundated rice systems. Lastly, rice varieties may need to be adjusted to the altered cultivation conditions, but breeding needs to be guided by agronomic and physiologic research.

2.1 International debate on water for food, nature and people

Over the past years, the first and second World Water Conference have catalyzed much political and scientific debate on the use of water to meet the growing needs of the global human population and of natural ecosystems. During the first conference in Marrakech in 1997, the need was felt to create public awareness on this matter. This materialized in the second Conference in The Hague in 2000 and various vision documents. The overall document described the challenges ahead in a 'Global Vision on Water, Life and the Environment for the 21st century' (Cosgrove & Rijsberman, 2000). The international debate was further structured along three vision documents on the themes: water for food and rural development, water for nature, and water for people. The latter theme emphasizes drinking water and sanitation (Anonymous, 2000). The vision on water for nature makes a case for the benefits of freshwater and related ecosystems to humankind, where intrinsic values of these systems are respected and preserved (IUCN, 2000). The vision on water for food and rural development centers on the need to assure adequate nutrition and to secure livelihoods (Van Hofwegen & Svendsen, 2000).

The documents recognize the high priority to improve water use efficiency in agriculture, as this sector is the largest consumer of water. Water scarcity problems are, therefore, primarily a food problem. Two major categories of solutions are advocated to produce 'more crop per drop'. First, through improving agronomic practices by improved crop varieties, substitution of crops and improved cultivation practices. Secondly, through better water management by improving irrigation water management, using more deficit, supplementary and precision irrigation, and reallocation of water from lower- to higher-value uses.

In the past, much emphasis has been placed on increasing food production through irrigated cultivation. Irrigated production indeed provides the bulk of the world cereals (FAO, 1996). Production was boosted to top levels, even in (semi-)arid regions, such as in North India and North

Mexico, where large-scale dams have created reservoirs for irrigation. These wheat, rice and maize baskets of the world have contributed substantially to the total global food production and are likely to maintain that role (Bindraban, 1997; Evans, 1998; FAO, 1996). Currently, irrigation accounts for about three-quarter of global water withdrawals and irrigated agriculture contributes nearly 40% of world food production on 17% of the cultivated land (FAO, 1996). Improper crop irrigation management and inadequate understanding of regional water flow and distribution result, however, in inefficient water use. Over time these inefficiencies may develop into problems that deteriorate soil productivity, such as soil salinity (e.g. Agarwal & Roest, 1996).

In the future, irrigated systems should comply with more sophisticated and responsive irrigation services with more equitable and timely deliveries under specific rights and management by smaller entities, and with charges for deliveries (Evans, 1998). This is needed to improve water use and crop production in irrigated systems. New developments in information technologies, remote sensing and crop modelling and in participatory approaches create powerful tools to assist in increasing regional water use efficiency by improving the temporal and spatial irrigation water distribution to meet crop demand in interaction with farmers (e.g. Bastiaanssen, 1998). Scope for improvement can be found in technical aspects, such as lining or covering canals, but may be beyond the resources of developing countries who use 70% of world's irrigation water. Much gain can be made through a better communication between engineers and farmers to optimize distribution to demand. Progress is made in this area through implementation of approaches such as Integrated and Participatory Irrigation Management (e.g. Mollinga, 1999). The attention to increase water use efficiency in irrigated systems is eminent but has been over-emphasized during the World Water Fora. International debates are dominated by the 'water sector', i.e. actors from the irrigation and drainage arena, who run capital-intensive enterprises.

Clearly under-exploited is the option to realize substantial improvements in water use efficiency, which can be obtained in rain-fed production, in inundated rice cultivation and through the use of novel technologies. After all, rain-fed systems account for 60% of the world food production. Though there is much international debate on the use of new technologies in life sciences, only little attention is paid to the use of these techniques for increasing crop production, e.g. by incorporating processes that govern C4 metabolism into C3 crops or incorporating nitrogen fixing characteristics non-leguminous crops. In addition, no attention is given to the possibilities of plant production under marine conditions, which would bring closer the exploitation of the world's largest ecosystem (Bindraban & Roest, 2000; Bindraban, 2000).

An interesting opportunity to reduce water use for food production may come from the current practices of inundated rice cultivation. Rice is the most important contributor to the global food basket and plays a major role in irrigated agriculture. Since approximately 3000 BC, rice in South East Asia has been cultivated under inundated conditions. This production system requires large amounts of water and labor, but has been very successful in feeding large populations for many centuries. More recently, the Green Revolution boosted rice production, but also further increased its dependence on water. Now that water becomes scarcer and labor opportunities are available outside agriculture, traditional rice cultivation practices are being reconsidered. The major rice baskets of China, South India, and Indonesia no longer enjoy unlimited water supply (Table 2.1). Recently, these countries are experimenting with rice production using less water. The objective of this paper is to give a concise overview of the factors and developments that catalyze transition of inundated and transplanted rice cultivation practices.

2.2 Converting inundated rice into dry rice

2.2.1 General

Transplanting rice under wet conditions is the major practice in rice cultivation. Economic factors, such as rising labor costs, and increasing competition for natural resources have enforced the need for less labor-, water-, and land-demanding rice cultivation practices. Advances in rice technology over the past decades have already facilitated transformations of inundated transplanted rice cultivation into direct dry or wet seeding.

Apart from saving water and raising grain yields, any system of non-flooded rice cultivation may bring other advantages such as maintenance of soil structure beneficial to non-rice crops in the rotation. Rice growth in aerated soil will also reduce methane emission, identified as a major contributor to the greenhouse effect. On the other hand, weed problems and hence the need for more labor or herbicides may increase in non-flooded rice cultivation, and may hamper further spreading of this system. The method requires a much larger degree of water control than flooding methods. So, there are technical, economic and social organizational issues to be addressed (Klemm, 1998). In addition, reduced water use at the field and farm level may provide new opportunities for water use in other regions or sectors. However, storage and redistribution of water may be required to make water saved in one area available in other areas. In addition, dramatically changed agronomic conditions may necessitate adaptation of rice varieties.

2.2.2 Labor requirement and direct seeding

Labor requirement in inundated rice systems approximates 1500 hours for a complete crop cycle (Table 2.2). Collier (1979) showed with data from Java that this requirement has not changed over time, also not with the introduction of High Yielding Varieties. Already in the early 1980's the call for reducing labor requirement was present. An analysis in Java showed that introduction of mechanization would reduce labor requirement, but would cause little unemployment because of opportunities outside the agricultural sector (Santoso, 1981).

Table 2.1. Changes in per capita water resources in selected Asian countries.

Country	Per capita available water resources (m^3)		
	1955	1990	2025
China	4597	2427	1818
India	5277	2464	1496
Vietnam	11746	5638	3215
Thailand	7865	3274	2477
Philippines	13507	5173	3077
South Korea	2940	1452	1253
Pakistan	10590	3962	1803
Nepal	19596	8686	4244
Sri Lanka	4930	2498	1738

Source: Hossain & Fischer (1995)

Table 2.2. Labor requirement for various operations in rice cultivation.

	Hours ha^{-1}
Field preparation	660
Planting seeds in seedbed	100
Transplanting	100-400
Weeding	300
Harvesting	300
Drying	100
Total	1560

Various sources: Collier, 1979; Shanthi et al., 1998

Increasing labor scarcity for transplanting caused many farmers during the 1980's en 1990's to shift to direct broadcast seeding of rice under wet or dry conditions. Long-term trends, such as declining real prices of rice and herbicides and increased labor costs for transplanting and weeding, have stimulated the practice of direct seeding. Simultaneous changes that have favored the switch include the release of modern rice varieties with high seedling vigor and tillering ability that increase the crop's ability to compete with weeds, improved water control and increased availability of selective herbicides (De Datta & Nantasomsaran, 1991).

Yield performance and biomass production hardly differs between transplanting and broadcast sowing (e.g. Shanti *et al.*, 1998). Land preparation for broadcast seeding under wet conditions is essentially similar to that for transplanting and does not affect the demand for labor. Direct seeding does, however, aggravate weed problems, resulting in an increase of herbicide use. Depending on the system, direct seeding instead of transplanting can reduce labor requirement by up to 50% (Shanti *et al.*, 1998). Farmers may, however, end up using most of the labor saved to control weeds. Though total labor demand shows no substantial reduction, the demand for labor is spread over a longer period of time than with transplanting. This allows farmers to make full use of family labor and to avoid bottlenecks (Pandey & Velasco, 1999).

2.2.3 Land pressure and multiple cropping

Rice production must increase by more than 40% over the coming 30 years to meet world demand (Hossain & Sombilla, 1999). The production increase should be realized on less land. Much agricultural land, including rice land, is already being lost to urbanization and soil degradation (Brown, 1995; Oldeman, 1999). Productivity can be increased by intensified land use through multiple cropping.

The water constraints may induce policies to relieve marginal lands for rice cultivation and to move from intensive rice-rice to rice-non-rice cropping patterns. Much emphasis is currently placed on rice-wheat cultivation. In India, the area under rice-wheat cropping increased from 4 million ha in 1960 to over 9 million ha in 1990 (Abrol, 1999). Increasing pressure on land pushes the introduction of potato cropping into these systems. Potatoes have become one of the fastest growing commodities in tropical and subtropical regions. India alone has increased its potato production fivefold in the last three decades, and it is the largest potato producer in the Indo-Gangetic Plain.

Cultivation of rice under dry conditions favors the inclusion of non-rice crops in the cropping system. Generally, puddling of soils increases bulk density and decreases hydraulic conductivity. While it facilitates rooting of the rice crop, it jeopardizes root development of consecutive crops. In rice-wheat systems, wheat yields are suppressed by the soil conditions caused by puddling. Bajpai & Tripathi

(2000) found puddling and non-puddling to be equally effective to rice, i.e. rice yields did not decline significantly. Non-pudling of rice produced significantly higher wheat yields than wheat following puddled rice cultivation. They, therefore, conclude that direct drilling of rice instead of puddling, combined with conventional tillage for wheat is beneficial for rice-wheat systems.

2.2.4 Water scarcity and water-saving rice production

Experiments on low water-input rice systems are far from conclusive. Early experiments done at the International Rice Research Institute (IRRI) by De Datta (1981) showed that substantial water savings could be realized (56%) but this resulted in a proportional yield reduction of 57%. Later, using upland varieties, the yield reduction stabilized at 37%. A review of experimental data from the seventies and eighties by Bouman & Tuong (2001) suggests a trade-off between water and yield compromising land requirement for production.

Recent experiments demonstrate that the decline in rice yield under non-flooded conditions is negligible. Bhagat *et al.* (1999) found that saturated soil conditions saved more than 40% water compared to continuos shallow ponding and produced the same rice yield when weeds were controlled by herbicides. They did find increased weed infestation, but argue that proper use of herbicide can substitute the excessive water consumption of continuously submerged rice fields.

In Madagascar, the 'System of Rice Intensification' (SRI) was developed where fields are kept un-flooded and the soil well aerated throughout the entire vegetative growth, while only a little water is kept on the field during the reproductive growth phase. While this may seem extreme, dramatic yield increases have been witnessed in Madagascar and some other countries. SRI prescribes a set of additional practices, including application of large amounts of organic matter, wide plant spacing, and the transplanting of very young seedlings. Yield increase is tentatively attributed to additive effects of water management, fertilization and timing of transplanting and by unexplained interactions. Experimental yield levels tripled from a starting point of approximately 2 t ha^{-1} (Uphoff, this volume). These results are encouraging but need further investigation, in particular to explore whether the advantages would also apply to higher yield levels, e.g. above 6-7 t ha^{-1}.

2.2.5 Global climate change and methane emission in rice fields

Methane is one of the principal greenhouse gasses with an estimated contribution to the greenhouse effect varying from 15 to 20%. The atmospheric methane concentration has more than doubled over the last century and shows strong correlation with global population growth, suggesting anthropogenic causes. It is estimated that wetland rice account for approximately 20% of the anthropogenic emissions (Denier van der Gon, 1996), but the uncertainty range runs from 4 to 20% (Van Bodegom, 2000). Wassmann *et al.* (2000a,b) report emissions from rainfed rice to correspond to only 20-40% of the emissions from irrigated rice. Based on the global distribution of the rice area, they assessed irrigated rice to account for 70-80% of total global methane emissions from rice cultivation, and the most promising target for mitigation strategies. Accurate assessments of regional emissions are however difficult, as management practices have a large impact on emission rates, and emission rates show non-linear responses to many factors (Van Bodegom, 2000).

The fact that management practices in inundated rice cultivation have a large impact on emissions creates, at the same time, a large number of options to make interesting contributions to reduce methane emissions. Factors that affect emissions are varieties, fertilizer type (sulphate containing), fallow, mulching, organic matter content, and water etc. (Wassmann *et al.*, 2000b; Minami & Takata, 1997; Husin *et al.*, 1995; Denier van der Gon, 1996).

Various experiments have been carried out to study the impact of water management on methane emission. In an experiment with intermittently flooding of paddy fields, Miyata *et al.* (2000) found increased fluxes of methane for drained paddies, compared to flooded conditions. This result is in line with findings of Denier van der Gon (1996), who shows an increased release of methane during 2-4 days after the soil fell dry. He estimated these emissions at 10-15% of the seasonal emission. These findings are also in line with results from Byrnes *et al.* (1995). Still, many studies report that introduction of midseason drainage and alternate flooding/drying reduces emissions by 30 up to 50% without compromising on yield (Lu *et al.*, 2000; Wang *et al.*, 2000). Adhya *et al.* (2000) found that conversion of rice-rice production systems into rice-non-rice could reduce emissions to one third only.

Singh *et al.* (1999) showed that the seasonal balances of methane emissions in dry land cultivation are not a source but a potential net sink of methane. The sink strength is potentially affected by the rice variety due to differential plant characteristics, length of period of soil saturation, and fertilization. Methane consumption showed a significant negative correlation to soil moisture content, for both control and fertilized conditions.

2.2.6 Changing practices, changing cultivars

Success in breeding for yield increase in rice during the 1960's and 1970's has been great for rice grown under inundated conditions, with effective irrigation facilities. Less successful was the development of varieties resistant to prolonged moisture stress and temporary submergence from heavy rainfalls (Hossain & Fischer, 1995).

Some scientists expect that genetic crop modifications may be needed to compensate observed yield declines when transforming inundated cultivation (Dat Van Tran, pers. comm.). Rice yield levels in upland cultivation may, however, be as high as in inundated cultivation. This suggests that sufficient genetic material is available to adjust current rice cultivars to cultivation practices with less water. In addition, better physiological understanding is needed before running into genetic adjustments.

Over the past decade, IRRI launched a program on 'super rice', to boost yield potential of rice. Success can unfortunately not be reported up to date. In designing this rice, much emphasis was placed on the morphological and photosynthetic characteristics (Peng *et al.*, 1994). While a large panicle was needed as sink, grains failed to fill adequately (Pulver & Nguyen, 1998). Earlier, Bindraban (1996; 1997) showed the eminent importance of a strong sink and hypotheses that the transport capacity of wheat could be limiting yield potentials in wheat. Simultaneously, research suggested that similar problems could apply to the super rice (Sheehy, pers. comm.). Emphasis in crop improvement may need to shift from increasing the source to increasing the sink and improving the vascular transport system. In the SRI system, Uphoff (this volume) found that early transplanting increased yield, with a positive association between tillering and grain filling, contrary to common finding. On the one hand, these positive relations are not uncommon at lower levels of production. On the other hand, this may point to the importance of the formation of the panicle and the transport system. In wheat, the double ridge stage, i.e. the transition of the apex from vegetative to generative, can occur already in 20 to 30 days after sowing (Slafer & Rawson, 1996; Gómez-Macpherson & Richards, 1997). The importance of the early days after emergence on yield formation is demonstrated by Jitla *et al.* (1997). Doubled CO_2 concentration from sowing onwards increased tiller number and yield. Delayed exposure to doubled CO_2 to 15 days after sowing still affected yield through enhanced sink while tiller number remained unchanged to control. They conclude that the results indicate that the generation of the sink in the floral apex plays an important role in determining grain yield. The above, shows that transplanting at 3-4 weeks after emergence can coincide with a critical phase of sink formation. This could mean that the transplanting shock may have a long-term damaging effect on the formation of the sink capacity and, therefore, on grain yield.

2.3 Discussion

Over the past decades, global and national developments have initiated research for alternative practices of inundated and transplanted rice cultivation. Increased labor scarcity has encouraged direct seeding, which does not cause reductions in yield and even increases return on investment.

Pressure on land for production causes cropping intensity to increase. Multiple cropping is of high value to many farmers as diversification reduces income risk and generates additional income. Conversion of inundated rice cultivation into cultivation practices with less water facilitates and enhances the production of other crops in the rotation.

The need to increase water use efficiency in rice production is pressing. Production loss in rice experiments with reduced water use in the past was substantial, but the need for detailed research was absent, because of a lacking pressure on more efficient water use. Recent results indicate that yield losses can be modest to non-existing and that new approaches, such as the SRI system, could even improve yield.

Cultivating rice under dry conditions reduces emissions of methane. Reducing methane emissions from rice fields through the introduction of dry cultivation practices cannot be the driving force for introducing the change. Ensuring food availability has priority over reducing methane emissions. However, simultaneous reduction in methane emissions in rice production systems using less water, could become an additional source of income for nations through emission trading.

Weed control has been one of the major driving forces behind inundated cultivation. Experiments on reducing water use for rice production all reveal increased weed competition. Although weeds can be controlled effectively by herbicides, the reliance on chemical aids reduces the sustainability of the production system, because of development of resistance, health hazards and environmental pollution. In the end, weed problems are also common for other crops, and ways should be found to sufficiently control its occurrence in rice.

Altered agronomic practices may necessitate adjusted rice varieties. Careful agronomic and crop physiological knowledge is, however, required to effectively guide the breeding efforts, either through conventional breeding or genetic modification.

Overall, it can be concluded that there is an increasing need to transfer inundated and transplanted rice production systems into less water- and labor-demanding systems, thereby facilitating multiple cropping and as a side-effect reducing methane emissions. Such systems may reduce income risks and increase farm household income, while water savings may increase total regional production. Clearly, much research is needed to overcome agronomic and crop-related problems.

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3. Water-saving rice cultivation in India

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Abstract

Rice is the staple food for 65% of the population in India. The crop accounts for about 22% (42 million ha) of the total cropped area, which is 34% of the area under food crops and 42% of the area under cereals. Rice yields vary strongly in time and space as a consequence of used cultivation methods under variable weather, ecological and socio-economic conditions. Of the total rice area, 19 million ha (45%) is irrigated and the remaining 23 million ha is cultivated under fragile rainfed conditions, often affected by erratic monsoons. While typical dryland rice is also grown in some areas during the monsoon season, semi-dry rice cultivation (dryland in the early stages and irrigated wetland situation when water becomes available) is also practiced. Rice yields are low in these rainfed areas. Many upland farmers plant local rices and use little fertilizers in soils that have low nutrient supply capacity.

Irrigated rice is also regularly affected by water stress due to inadequate irrigation water supply. Most water management research has been focussed on flooded rice, and limited work has been done on intermittent irrigation with returning aerated soil conditions. The general water management strategy recommended is continuous submergence with a water layer of up to 5 cm when the film of water disappears from the surface. In river delta areas, farmers cannot control the water level. Research on intermittent irrigation has demonstrated promise to produce comparable rice yields as under submergence. However, no systematic study has been done to grow rice with controlled irrigation as, for example, advocated in the System of Rice Intensification (SRI). A pilot trial conducted in Coimbatore (11° N 77° E) during 2000-2001 with SRI showed that soil fertility, plant density, methods of sowing, irrigation management, and weed control methods play a key role in the success of such systems. Successful demonstration of water-saving rice systems, both in conventional and non-conventional areas, would be extremely useful to India towards efficient utilization of scarce water resources. Growing rice like a dryland crop in typical flood-irrigated lands means a revolution in water management, but creating a suitable rice-soil ecosystem will be the challenge for its success.

3.1 Introduction

India is endowed with a rich and vast diversity of natural resources on which demographic pressure is mounting day by day. The present population of over 1 billion accounts for nearly 18% of the world's population, is estimated to increase to 1.4 billion in 2025 and 1.7 billion in 2050, needing annually 380 and 480 million ton of food grains, respectively.

Rice is the staple food for 65% of the population in India. The crop accounts for about 22% (43 million ha) of the total cropped area, which is 34% of the area under food crops and 42% of the area under cereals. India is the second largest rice producing country in the world. The annual rice production is 82 million ton and rice is the largest consumed calorie source among the food grains. With a per capita availability of 73.8 kg it meets 31% of the total calorie requirements. In addition, rice cultivation accounts for 30-50% of the agricultural income. Export of rice, which steadily increased from 0.4 million ton in the mid-eighties to 5.0 million ton by 1995-96, earns Rs. 30 billion through foreign exchange. Following the liberalization of international trade after the World Trade Agreement, Indian rice has become highly competitive and has been identified as one of the major commodities for export. Its availability is vital for national food security.

During the last 30 years, growth in rice production transformed food-deficient India into a surplus state (Fig. 3.1). Increased production was primarily possible due to the use of improved inputs such as high yielding varieties and fertilizers, and adoption of improved crop and pest management practices, which accounted for 76.7% of the growth.

To sustain present food self sufficiency and to meet future food requirement, India has to realize an annual growth in rice productivity of at least 3% to achieve a production target of 135 million ton in 2020. India needs to add at least 2.5 million ton of milled rice annually to sustain its present level of self-sufficiency.

Average rainfall in India is about 1120 mm. A large part of it (80%) is brought by the South-West monsoon and precipitates as high intensity rain from June to September. The rest of the year has very low rainfall except for the coastal belt of Tamil Nadu, Andhra Pradesh and parts of Orissa due to the North-East monsoon from October to December.

According to the National Commission on Agriculture (NCA, 1976), the country receives 356 million hectare meter (m ha m) water as rain and 20 m ha m via cross border flows. Of the total, approximately 215 m ha m enters the soil of which 165 m ha m is held as soil water and 50 m ha m drains deep and adds to groundwater resources. The remaining 170 m ha m is runoff and ends up in rivers. It has been estimated that only 69 m ha m of the river flow can be exploited for irrigation due to terrain characteristics.

Despite the annual average water input of about 400 m ha m, the country faces shortages of water due to erratic and uncertain rainfall both in space and time. Per capita availability of water at national level reduced from about 5177 m^3 in 1951 to currently 1869 m^3, with great local variation in water availability. The irrigation potential has increased from 22.6 million ha in 1951 to about 94.7 million ha (GOI, 2001). The total groundwater in India that is replenished annually is estimated to be about 43.2 m ha m yr^{-1} (432 billion m^3). It is estimated that 32.5 m ha m yr^{-1} is available for irrigation.

Approximately 51.6 m ha m water is used for rice cultivation, which is about 18.2% of the total available water. Rice uses a major part of the national fresh water reserves. Considering the future population growth, competition from non-agricultural uses of water and increasing demand for agricultural products, available water needs to be used efficiently. To reduce the share of water in rice cultivation, it is essential to identify new methods of rice cultivation for upland rice systems.

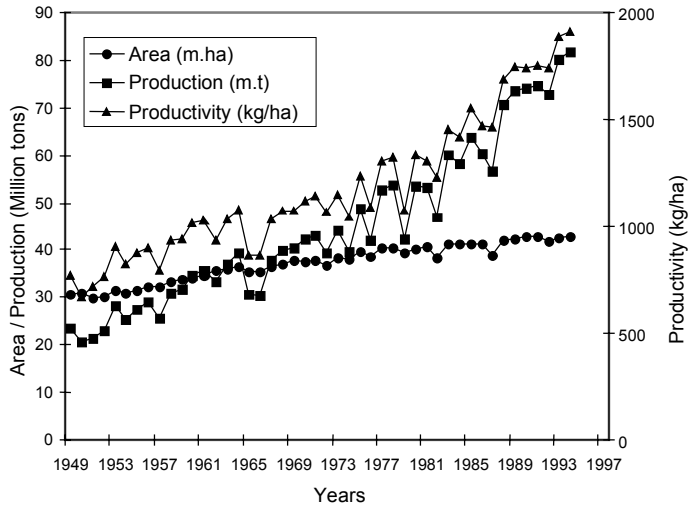


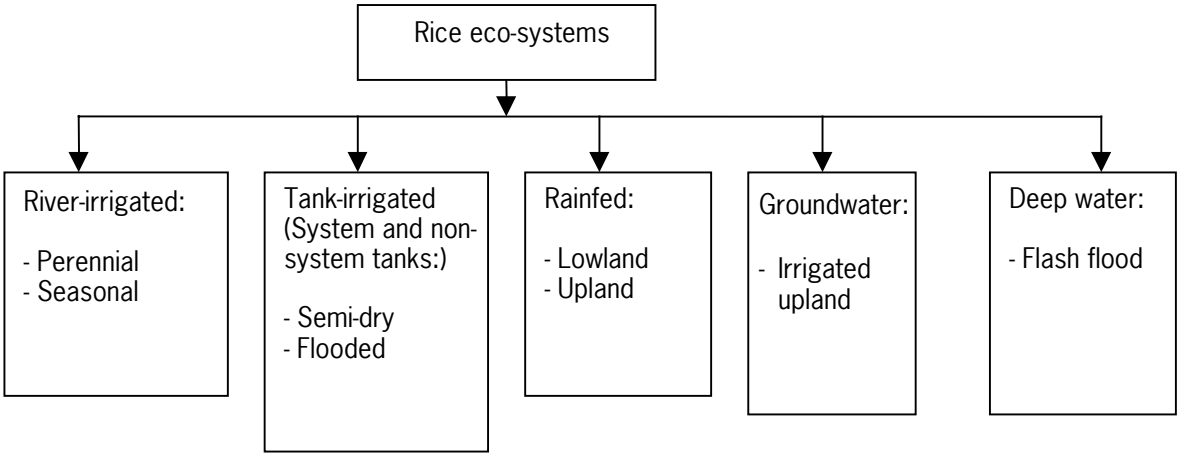
Figure 3.1. Rice area, production and productivity statistics in India.

The objectives of this paper are:

1. To review results of existing research on crop improvement and management related to water-saving rice cultivation (mostly in rainfed upland and water-scarce areas).
2. To explore the possibilities of strengthening the ongoing research efforts to explore the opportunities of water-saving rice production systems in India.

3.2 Rice eco-systems in India

Rice is grown in a wide range of agro-ecological zones from above sea level in the south to high altitudes in the north. Based on water availability and irrigation sources these eco-systems are classified as follows:



River-irrigated

Traditional rice cultivation is based on river water. In general, these areas are flood plains of rivers, which can be divided into: (1) rivers with perennial water flow and (2) rivers with seasonal water flow. In the second case, reservoirs built across rivers accumulate water from seasonal monsoon rains. Water is released depending upon the storage level and the growing season. Rice is cultivated when water is available in the rivers or reservoirs. Groundwater in these areas is also exploited for rice cultivation. In some years, low rainfall leads to low water storage in the reservoirs and crops face drought in later growth stages. Sometimes, to save standing crops, intermittent irrigation is practiced which also leads to partial drought. In some irrigation projects intermittent irrigation is the rule and water availability determines the supply of water in the field.

Tank-irrigated

Tanks built across slopes to catch rainfall act as small reservoirs. Water accumulation in the tanks depends on the rain received in the catchment. In these areas, rice cultivation is very common if sufficient water is available. In some situations, rice is started as a 'dry crop' with direct seeding and it grows as a rainfed crop. When tank water becomes available the crop is continued as a lowland irrigation crop. This typical 'semi-dry' rice cultivation is popular in certain areas of Tamil Nadu. Monsoon rains determine the productivity of the crop.

Groundwater-irrigated

Some farmers solely depend on available groundwater for rice cultivation. These are typical upland rice eco-systems.

Rainfed

Rainfed rice can be divided into two categories. In parts of Eastern India, during the rainy season, rice is cultivated as an upland rainfed and lowland rainfed crop. These areas, exclusively, depend on monsoon rainfall.

Deep water/flash flood

Deep water rice cultivation is practiced in the Eastern part of India in low lying areas prone to regular flood. The depth of water varies from 30 to 100 cm. The type of irrigation followed in this system is flash flood without water control. Rice varieties suitable for deep water conditions have been developed.

Based on the crop establishment method, rice eco-systems are classified into:

1. Dry seeded: Seeds are sown under dry conditions and then irrigated like an upland irrigation crop when water is available in tanks after the start of the monsoon season. The system is also known as semi-dry paddy cultivation.
2. Wet seeded: Sprouted seeds are sown under wet puddled conditions as direct sown crop. The system is also known as direct wet-seeded lowland or upland rice.
3. Transplanted: This system of rice cultivation is widely practiced in India. Rice seedlings are grown in nurseries and 25- to 30-days old seedlings are transplanted to the main field.

Efforts are being made to popularise each of the crop establishment methods across the major rice eco-systems based on their suitability and social preference. Placement (seedling throwing) of seedlings on puddled soil is also advocated where labour shortage is a severe problem.

3.3 Rice production under rainfed conditions

Upland rice is an important system of rice cultivation in India. This type of cultivation has a great potential in various regions. However, it has some constraints, such as uncertain rainfall and high evaporative demand causing moisture stress. Even in river areas, where irrigation sources are canals or tank systems, water availability is uncertain due to limited storage after insufficient rainfall. This situation creates highly variable yields. A reasonably stable rice production in India is only realized in four areas (coefficient of variation is less than 15%): the coastal areas facing the Arabian Sea and the Assam valley receiving over 2000 mm of rainfall annually, and the Eastern coastal region and West Bengal, both located in large alluvial plains receiving less than 2000 mm rainfall. The regions where rice production is most variable are found in North-East India and the East Coast. When annual rainfall falls below 2000 mm, production is highly variable in these regions. Although annual rainfall is less than 1000 mm in the Southern peninsular, production variability is not higher than in the northern half of the eastern coast because of a larger irrigated area.

Rice is sown and harvested almost year round in India. The largest proportion is monsoon dependent. Fig. 3.2 shows the sowing and harvesting periods in each state. About 6 million ha rice is grown under rainfed conditions (700-1100 mm) during July-September (Fig. 3.3) (Murthy & Ramakrishnayya, 1982). In the extreme south, comprising the state of Tamil Nadu, about 0.4 million ha is under rainfed rice cultivation during the North-East monsoon season (October-January). Generally, early maturing rice cultivars (80-110 days total duration) are planted. Although the early crop receives adequate rainfall to mature, it often is subject to droughts which last up to 10 days. Almost the entire 42.5 million ha rice in India (Table 3.1) is subject to water stress, i.e. 41.15 million ha (96.8%).

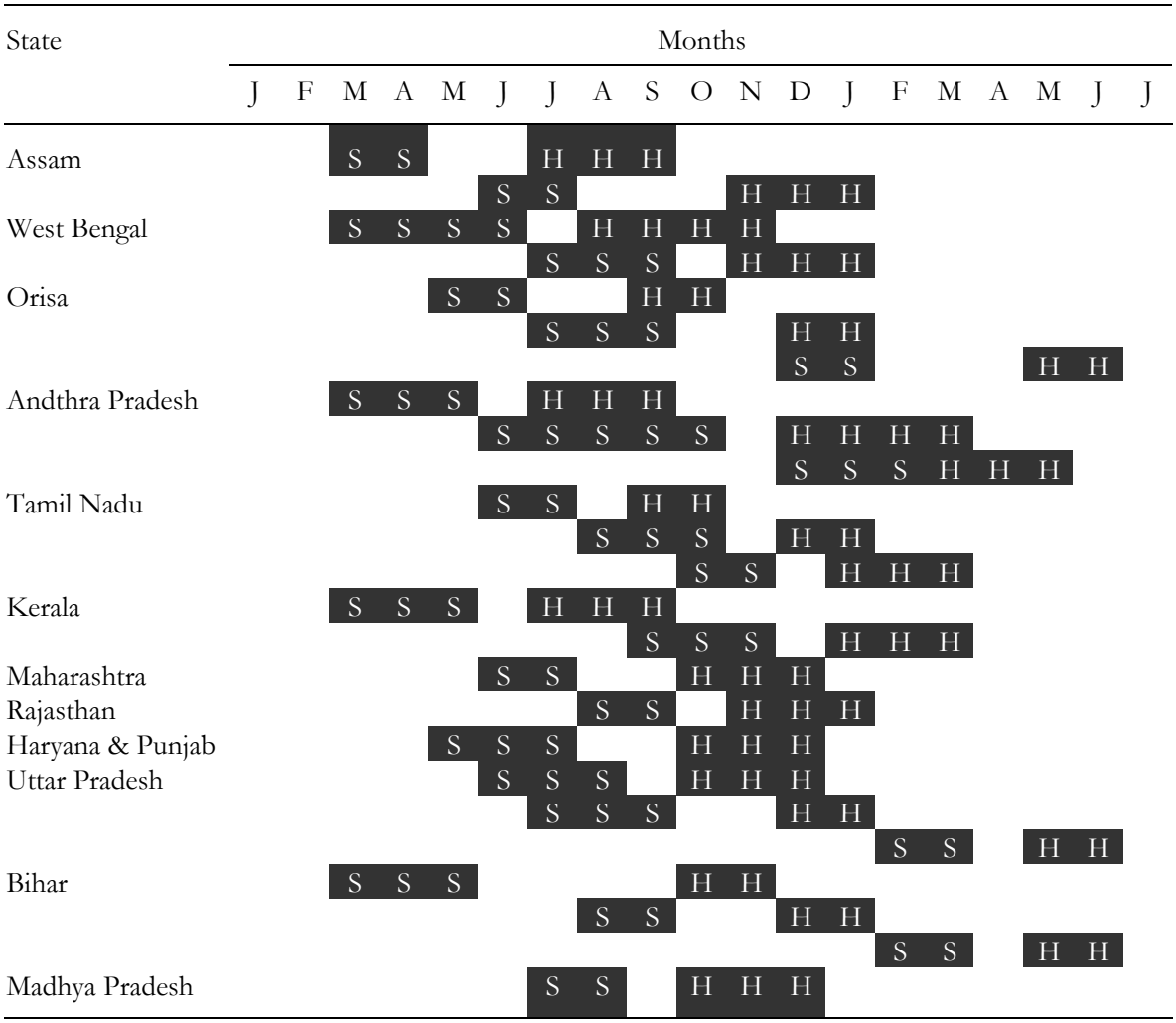


Figure 3.2. The rice cropping calendar in various states of India (S and H stands for Sowing and Harvesting, respectively).

Table 3.1. Rice area in India under different water availability conditions (Huke & Huke, 1997).

Water availability conditions	Area (million ha)	Percentage of total
Deep water (> 100 cm)	1.36	3.2
Irrigated	19.66	46.2
Rainfed	21.49	50.6
Total rice area	42.52	-

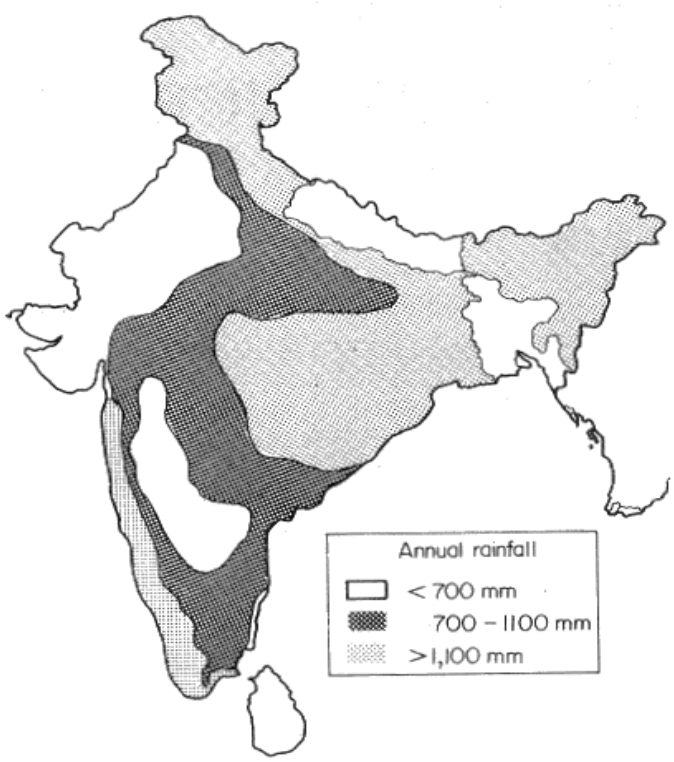


Figure 3.3. Drought prone rice areas in India (Murthy & Ramakrishnayya, 1982).

3.4 Drought tolerance in rice

3.4.1 Morphological characteristics

Significant variety differences exist with respect to drought tolerance. In general, upland rice cultivars are more tolerant to drought than lowland types due to morphological differences (De Datta & Beachell, 1972). A low tillering habit under various soil moisture conditions is a distinctive feature of upland rice. When soil moisture availability is the main limiting factor, a low to medium tillering habit helps upland rice to maintain a plant density that can cope with water deficiency. In general, moisture stress results in reduced plant height. Reduction in plant height is more pronounced in lowland and susceptible types, rendering them relatively more prone to drought effects than the upland and drought tolerant types (Table 3.2).

Inheritance of drought tolerance is a complex phenomenon and there exists no proper method to determine it. A number of morphological and physiological parameters like spreading habit of the plant, deeper and thicker root system, good expression of the panicles, leaf rolling, canopy temperature, high root/shoot ratio, high moisture content in the shoot and high osmotic pressure in the root, etc., have been used for screening varieties for drought tolerance. Foliage colour was found associated with drought resistance. Light green plants were found to resist drought better than dark green plants (Rajagopalan, 1957).

Soil moisture deficit reduces plant height and tiller number (Ramakrishnayya & Murthy, 1991). However, reduction in crop growth and yield depends on the degree and duration of water deficit and growth stage of the crop. Upland rice is more sensitive to water stress at the reproductive stage than at the vegetative stage (Murthy, 1987). Tillers produced till the end of drought were most productive and contributed to yield, whereas those developed during the recovery phase did not affect yield.

Table 3.2. Reduction of plant characteristics of different types of rice under dry conditions compared to flooded conditions (Basu Raychaudhuri & Das Gupta, 1981).

Types of rice	Reduction compared to flooded conditions (%)			
	Tillers/hill	Plant height	Leaves/hill	Average leaf area
Traditional upland rice	10.8	10.1	15.1	10.1
Semi-dwarf upland rice	23.4	16.8	11.0	8.1
Drought tolerant rice	16.3	6.6	21.2	0.3
Semi-dwarf lowland rice	46.0	12.5	52.3	21.4
Drought susceptible rice	41.9	14.9	13.6	25.0
Mean	31.8	11.5	27.5	13.9
SEM ±	7.1	1.6	7.9	3.8

3.4.2 Root characteristics

High root density and root weight, and the growth duration of a crop are important characteristics for selecting drought tolerant genotypes. Early genotypes with high root density at maturity give higher yields under rainfed situations (Jeena & Mani, 1990).

Upland and drought tolerant types have predominantly long and thick roots, densely formed at the crown, and many deep roots (Table 3.3). Deep penetration of roots is one of the most effective means to avoid drought (De Datta & Beachell, 1972). Under dryland conditions, rice depends on both shoot and root characteristics for its nutrition and growth. When water is uniformly supplied to all soil layers, rice roots extract water preferably from shallow layers (Fig. 3.4). As the soil water potential in the surface decreases, water retained in the deeper layer contributes more to evapotranspiration. Information on the effect of plant density on root characteristics is not well-known, although roots play a crucial role in moisture extraction. Rao *et al.* (1992) revealed that increased plant density in rice decreased the drought resistance period particularly at 100 and 200 hills m^{-2}. Increased plant density reduced volume, weight and number of roots per hill, though these characteristics increased per unit of area.

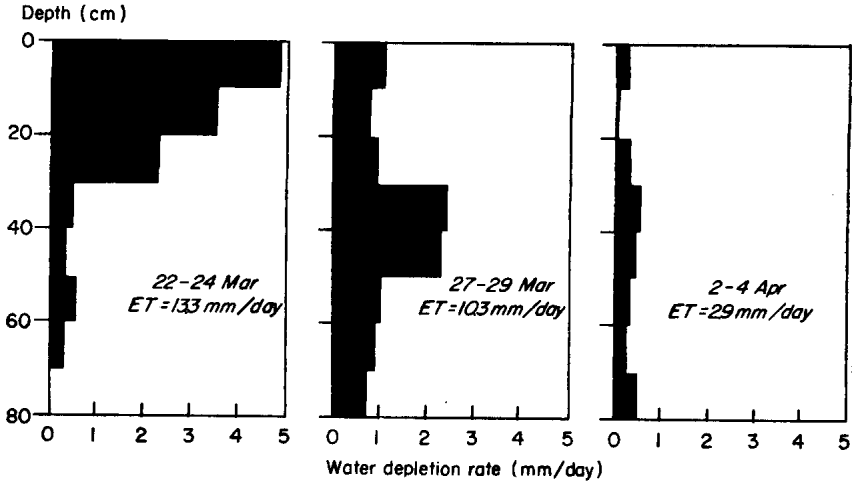


Figure 3.4. Water extraction pattern of rice with respect to water potential in the surface layer (Yoshida & Hasegawa, 1982).

Table 3.3. Root characteristics of different types of rice and their reaction to drought under direct sown upland conditions (Basu Raychaudhuri & Das Gupta, 1981).

Types of rice	Root length (cm)	Diameter (mm)	Root-shoot ratio (70 DAS) [1] (mg 1000 mg $^{-1}$)
Traditional upland rice	17.6	0.71	196
Semi-dwarf upland rice	16.1	0.85	196
Drought tolerant rice	18.9	1.04	251
Traditional lowland rice	14.5	0.78	168
Semi-dwarf lowland rice	12.5	0.71	131
Drought susceptible rice	9.9	0.55	60
Mean	14.91	0.77	167
SEM	1.37	0.07	26.7

[1] *DAS = Days After Sowing*

3.4.3 Phenological development

The term moisture stress is generally used for moisture-deficit conditions, but does not affect all aspects of plant growth and development equally. Grain yield of a crop is the integrated result of the effect of stress on water related processes, such as, photosynthesis, respiration, nutrition, growth and development.

The effects of water stress on source intensity (photosynthesis), source size (leaf growth), and sink size are equally or more important than the effects on other processes, especially in annual crops (Fig. 3.5). Rice is more susceptible to moisture stress during early seedling and flowering stages than other stages of growth and generally the reproductive stage is more affected than the vegetative stage. Water stress at the initial stages causes rice seedlings not to emerge until 13 days after sowing. Moisture stress at tillering causes maximum reduction in panicle number while grain sterility is more enhanced by water stress at both tillering and booting stage (Pathak *et al.*, 1999). Rice has less filled grains due to water stress at panicle development and ripening stages. Ingram & Yambao (1988) reported yield reductions due to water stress from 25 to 45% for 5-10 days of water deficit, and for 15 days losses may be as high as 88%. Thus, rice yields were affected more by the duration of drought than by the stage at which it occurred. Yields are reduced even at –15 to –20 kPa matric potentials (Sharma *et al.*, 1997).

In contrast, an experiment in an alluvial soil of the Mahanadhi delta showed that scheduling 7 cm irrigation water 6 days after disappearance of water, irrespective of the growth stages, gave rice yields comparable to those obtained with continuous flooding (3-7 cm) (Table 3.4). This schedule resulted in a net saving of 38 to 47% irrigation water and 60 to 88% increase in water-use efficiency (Jha & Sahoo, 1988).

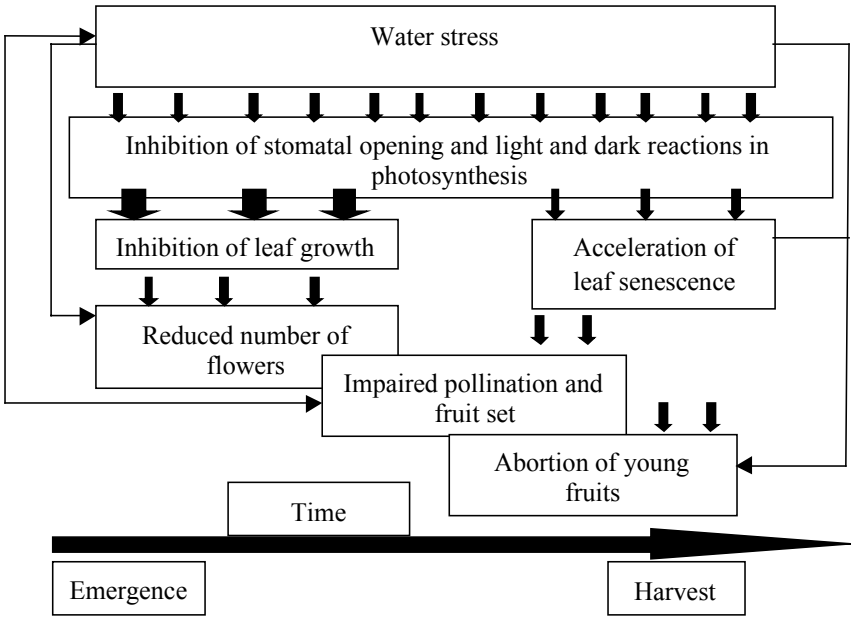


Figure 3.5. Effects of water stress on the physiological and morphological processes underlying source intensity, source size and sink size (Hsiao & Bradford, 1982).

Table 3.4. Yield, yield attributes, total water requirement and water use efficiency of rice as influenced by various treatments (Jha & Sahoo, 1988).

Treatments	Grain yield (t ha^{-1})	Panicle weight (g)	Water (mm) requirement	Water-use efficiency (kg ha^{-1} mm^{-1})
Continuous flooding (7 cm water)	4.6	1.27	1797	2.53
7 cm water applied on the day of disappearance of water	4.4	1.24	1437	3.08
7 cm water applied 2 days after disappearance of water	4.6	1.25	1227	3.77
7 cm water applied 4 days after disappearance of water	4.4	1.23	1087	4.75
7 cm water applied 6 days after disappearance of water	4.5	1.31	947	4.76
F test	NS	NS		

3.4.4 Plant water relations

The most useful measurements of water stress under field conditions are plant water potential and stomatal conductance/resistance. Irrigated rice in many parts of India is subject to water deficits resulting from inadequate or insufficient moisture supply and, therefore, experiences soil moisture conditions similar to that of rainfed rice.

Using different irrigation schedules, Singh *et al.* (1997) showed that rice plants grown under continuos submergence had higher leaf water potentials and stomatal conductance than plants grown under alternate wet and dry conditions, probably due to differences in incident PAR on leaves as well as better availability of moisture to the plants (Table 3.5).

Table 3.5. Effect of different irrigation practices on leaf water potential, stomatal conductance and radiation characteristics (Singh et al., 1997).

Treatment	Leaf water potential (-MPa)	Stomatal conductance (cm s^{-1})	Radiation (PAR) coefficients			Grain yield (t ha^{-1})
			Albedo from crop canopy (%)	Transmission through canopy (%)	Absorption (%)	
Continuous submergence (5 ± 2 cm)	1.80	0.446	4.9	4.5	90.4	4.96
Alternate wetting wilting	1.96	0.410	3.7	6.0	90.2	3.47
LSD (p=0.05)	-	-	-	-	-	1.02

Identification of genotypes showing low wilting (10-13%) and high Relative Water Content (RWC 70-75%) or genotypes with low wilting (10-20%) and low RWC (56-58%) could be used under upland conditions as drought avoidance or drought tolerance mechanism (Rao & Venkateswarlu, 1997). Correlations between RWC and wilting and drought tolerance indicated that higher tolerance or late wilting was highly desirable under drought conditions (Thangaraj & Sivasubramanian, 1990).

Relative water content of rice plants reduces significantly under submerged and puddled condition (Table 3.6). Poor root growth under submerged and puddled conditions affects water uptake (Mali & Varade, 1983).

Seed hardening before sowing is the best practice of crop management for drought tolerance. Seeds treated with 1% KCl can withstand a drought for 7-10 days. After this treatment, seeds are shade-dried and can be used for dry sowing after seed treatment with fungicides and bio-fertilisers.

A study conducted in a clay loam soil of Coimbatore revealed that irrigation of semi-dry rice with a water layer of 5 cm at weekly intervals up to 45 and 60 days after emergence (DAE) was significantly superior compared to fortnightly irrigations. Seed treatment with Chamatkar at 125 ppm (mepiquat chloride 5 AS) with a foliar application of 0.5% KCl had a significant favorable effect on early vegetative growth (Table 3.7).

Table 3.6. Relative Water Content (%) of rice leaves as influenced by soil moisture (Mali & Varade, 1983).

Treatment	Relative Water Content (%)
Field capacity	79.23
Hair cracking	79.92
Submergence	76.15
Puddling with submergence	74.97
CD (p = 0.05)	1.96

Table 3.7. Effect of different irrigation practices and seed hardening on semi-dry rice yield (ADT 36) at Coimbatore (Asokaraja, 1998).

Treatments	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})
Weekly irrigation up to 45 DAE[1]	5.22	6.54
Fortnightly irrigation up to 45 DAE	4.43	5.54
Weekly irrigation up to 60 DAE	5.05	6.31
Fortnightly irrigation up to 60 DAE	4.30	5.38
CD (p = 0.05)	0.06	0.08
Control – no seed hardening, no foliar spray	4.05	5.07
Seed hardening-Chamatkar 125 ppm	4.71	4.89
Chamatkar 125 ppm + foliar spray KCl 0.5%	5.33	6.66
No seed hardening + foliar spray KCl 0.5%	5.02	6.28
Seed hardening with water	4.64	5.81
CD (p = 0.05)	0.08	0.08

[1] *DAE = Days After Emergence*

3.4.5 Selection of suitable varieties

Specific varieties for various environmental conditions are required. Early maturing varieties are more essential for rainfed rice cultivation than for irrigated rice cultivation. Varieties should mature in 90-105 days so as to complete their life cycle well before the recession of the monsoon. They should tolerate moisture stress during the early growth and have great translocation efficiency after flowering.

Garrity *et al.* (1982) suggest the following agronomic and physiological genotype characteristics for direct seeded rainfed rice:

- High and stable yield.
- Early vegetative growth and vigour with wide droopy leaves to suppress weeds.
- Tolerance to drought and intercropping situations.
- Non-lodging under inundated conditions.
- Recovery capacity after drought spell.

Paddy varieties, such as PMK 1, PMK 2 and MDU 5 are some of the drought tolerant varieties developed for rainfed situations of Tamil Nadu. The comparative performance of the improved varieties and land races (Jeyaprakash, 1998) showed that land races had yields of about 1000-1600 kg ha^{-1} whereas improved varieties had yields of 2600 kg ha^{-1} (PMK-1) and 3200 kg ha^{-1} (PMK-2). Land races are still preferred since they are highly resistant to drought and to other biotic stresses. But they are tall and lodge easily, and have low yields (Table 3.8). Due to the decreasing cultivated area and population increase, there is a need to develop improved varieties with high yield potentials coupled with resistance to major stresses occurring in rainfed situations.

Table 3.8. Performance of land races and improved varieties (Jeyaprakash, 1998).

Land races and improved varieties	Grain yield (kg ha^{-1})
Land races:	
Norungan	1580
Mattaikar	1000
Varappukudankar	1112
Kallurandaikar	1500
Vellaichitraikar	1567
Chandikar	1534
Kuliadichan	1601
Sivappuchitraikar	1047
Improved varieties	
PMK – 1	2600
PMK – 2	3200

Breeding work has to be concentrated on developing early rice varieties with a maturation period of 85-90 days to be suitable for major rainfed regions.

3.5 Seeds and sowing

3.5.1 Seed treatment

Biological fungicides like *Trichoderma viridi* can be applied at 4 g kg^{-1} seed. Seeds can also be treated with chemical fungicides like carbendazim at 2 g kg^{-1} seed. If sufficient soil moisture is available, seeds can be treated with bio-fertilisers like azosprillum and phosphobacteria, 600 g each. These bio-fertilisers support young seedlings to take up nutrients. If moisture is insufficient, these bio-fertilisers can be applied mixed with farmyard manure or sand at 2.5 kg ha^{-1} after onset of the rains.

3.5.2 Seed rate

Increasing seed rates under rainfed conditions decrease the weed population as well as weed dry weight (Table 3.9). A seed rate of 100 kg ha^{-1} (127 plants m^{-2}) showed highest grain yields (Shrivastava & Tripathi, 1993).

In vertisols of central India, one-third increase in plant density (15 x 10 cm) gave significantly higher yields (7.79%) than planting at 20 x 10 cm (Pandey & Tripathi, 1993). In the same area, under Alfisols, increasing the number of seedlings from 3 to 6 hill^{-1} did not increase the yield of rice under rainfed transplanted conditions (Paraye & Kandalkar, 1994).

Table 3.9. Effect of plant density (seed rate) and weeding operation on weed density and weight, and rice yield (Shrivastava & Tripathi, 1993).

Treatment	Weed population (m^{-2})	Weed dry weight ($g\ m^{-2}$)	Grain yield ($t\ ha^{-1}$)
Country plough with blunt shear	114.6	132.6	4.59
Three tine wooden harrow	114.2	133.6	3.73
CD (p = 0.05)	NS	NS	0.36
Seed rate ($kg\ ha^{-1}$):			
80	130.0	157.0	3.83
90	127.0	140.6	4.19
100	112.0	128.6	4.45
110	109.6	128.0	4.18
120	94.0	111.0	3.96
CD (p = 0.05)	0.9	1.3	0.19

3.5.3 Sowing time

Optimum sowing time is very important for upland and water-saving rice cultivation. As most of the rice is being grown in the kharif season (June-September) in Northern India, the sowing time is very important to avoid possible water stress. In the uplands of the Northern hill regions of India, crops sown on March 15 realized 12.5 and 34.5% higher grain yields than crops sown on March 30 and April 15 (Table 3.10), respectively, due to more spikelets, grains per spike and higher 1000 grain weight (Singh & Prasad, 1999). Sowing on March 30 and April 15 reduced the growth rate by 25 and 32 $kg\ ha^{-1}\ d^{-1}$, respectively, compared to sowing on March 15.

Similarly, Singh *et al.* (1991) showed that timely sowing of rainfed rice at the onset of monsoon (at Ranchi, Bihar) in a sandy loam soil, contributed most to yield increase following fertilizer and weed control among all factors tested. The yield increase due to timely sowing was 381 $kg\ ha^{-1}$ compared to late sowing in farmers practice (Table 3.11).

Table 3.10. Effect of sowing date on grain and straw yield of spring sown rice (Singh & Prasad, 1999).

Sowing date	Grain yield ($t\ ha^{-1}$)	Straw yield ($t\ ha^{-1}$)
March 15	3.31	4.62
March 30	2.94	4.18
April 15	2.46	3.53
CD (p = 0.05)	0.35	0.28

Table 3.11. Yield (attributes) of rainfed rice as influenced by production factors under farmers' practice (Singh et al., 1991).

Treatment	Effective tillers m^{-2}	Filled grains (%)	Grain yield (t ha^{-1})
Farmers' practice (FP)	132	70.9	0.652
FP + land preparation	161	79.9	0.812
FP + organic manure	167	86.6	0.922
FP + improved variety	135	71.3	0.680
FP + optimum seed rate	134	70.9	0.690
FP + timely sowing	173	89.7	0.986
FP + line sowing	157	69.2	0.640
FP + optimum row direction	158	70.2	0.663
FP + fertilizer	179	91.0	1.160
FP + irrigation	150	71.0	0.821
FP + weed control	177	90.5	1.034
FP + plant protection	142	70.8	0.682
CD at 5%	26	1.2	0.171

3.5.4 Seedling emergence and survival

Two weeks after seeding, most varieties sown in a soil below field capacity (35% soil moisture, 7 days after the soil reached field capacity) had higher seedling emergence than those sown at field capacity (46% soil moisture). But at field capacity, most modern varieties emerged better than traditional upland varieties (Haque & Islam, 1987).

Seedling survival is a severe problem in drought prone areas, especially during the early growth stages. Suryaprakasha Rao & Venkateswarlu (1989) concluded that besides drought resistance, fast recovery of seedlings also constitutes an important trait in screening genotypes for drought prone areas.

3.6 Change in soil chemistry

Soil pH and electric conductivity in near-saturated conditions were slightly lower than in water-stressed conditions of alkaline soils of central India. In saturated conditions, soil profiles were almost wet and due to continuous dilution, pH and EC were lower. However, under water-stressed conditions, greater depletion of available soil moisture before each irrigation resulted in accumulation of salts and, subsequently, increased electrical conductivity.

Puddling decreases Eh and increases soil pH and electrical conductivity of the soil solution, thus creating reduced conditions (Gildyal & Tripathi, 1971). Puddling also reduces percolation losses from rainfall (De Datta *et al.*, 1978); irrigation decreases nitrogen requirements (Sanchez, 1973) and helps to maintain high amounts of Zn in the soil.

3.7 Nutrient management in water-saving systems: Possible alternatives

Soils of water-saving systems may be coarse textured with low fertility or heavy textured with high fertility. Soils with a variety of physical and chemical characteristics are widespread in highly favourable and unfavourable rice eco-systems. In water-saving systems, soils are exposed to alternate wetting and drying. Therefore, aerobic situations occasionally exist under such conditions. Dry soil conditions often result in low yields which are attributed to nutritional disorders (Singh & Bhattacharyya, 1989). Organic

matter decomposes quickly under aerobic conditions where soil moisture and temperature are not limiting. In contrast, under anaerobic situations the rate of decomposition of organic matter is low and produces a variety of substances like CO_2, organic acids, methane, ammonia and hydrogen sulphide. In some cases, submerged conditions with puddling delay decomposition of organic matter leading to accumulation of toxic organic compounds, carbon dioxide, methane, ferrous iron and free hydrogen sulphide, thus affecting growth and yield of rice (Das & Mandal, 1986). When reduction of soils does not take place under aerobic conditions, phosphorus becomes unavailable and can be limiting in upland soils particularly in strongly acid oxisols. Under aerobic situations, more nitrogen is mineralised with sufficient moisture availability. But in upland situations with moisture stress N availability is low. Phosphorus is deficit in acid soils due to high fixation, and in strongly acid soils, aluminum and manganese often reach toxic levels.

3.7.1 Nitrogen

Application of N up to 100-150 kg ha^{-1} increased yields of rice under water deficit conditions. However, 50 kg N ha^{-1} did not show any effect on yields under prolonged moisture stress. Spikelet sterility increased and grain/straw ratio decreased with increasing N levels, suggesting that use of high N doses should be avoided under prolonged moisture stress (Sharma *et al.*, 1997). Pradeep *et al.* (1994) reported significant effects of both irrigation and N on rice grain yield in a sandy loam soil (Table 3.12).

However, significant differences were only shown compared to the rainfed control. Treatments based on 3, 5 and 7 days drying after disappearance of ponded water were similar. Rice showed a yield increase up to 80 kg N ha^{-1} and there was no interaction between irrigation and N. In a clay loam soil Ram *et al.* (1985) reported a significant yield increase up to 60 kg N ha^{-1}.

With modern rice varieties N fertilizer applications in upland systems are crucial to realize high yields. In upland systems, the efficiency of fertilizer N is usually low. Upland rice soils are highly sensitive to nitrification. The use of nitrification inhibitors may increase N use efficiency. Another approach to increase the efficiency of fertilizer N is through split application (Table 3.13). But occurrence of drought at the time of second or third split of N may lead to greater N losses.

Table 3.12. Effect of water and N application practices on yield, growth, water use efficiency and N uptake of direct seeded upland rice (Pradeep et al., 1994).

Treatments	Grain yield (t ha^{-1})	Leaf Area Index at 90 DAS	Total N uptake (kg ha^{-1})	Water use efficiency (kg m^{-3})
Water regimes				
3 days drying after 7 cm irrigation	3.43	3.35	71.6	0.253
5 days drying after 7 cm irrigation	3.37	3.31	72.0	0.262
7 days drying after 7 cm irrigation	3.07	3.25	67.9	0.252
Rainfed	2.49	3.11	59.1	0.231
CD (p = 0.05)	0.44	0.13	9.3	NS
N-applied (kg ha^{-1})				
0	2.34	3.05	47.4	0.189
40	2.89	3.17	63.1	0.234
80	3.41	3.34	75.6	0.276
120	3.70	3.46	84.5	0.299
CD (p = 0.05)	0.44	0.13	9.3	0.036

Table 3.13. Number of panicles and yield as influenced by fertilizer treatments (Mishra & Lal, 1994).

Treatments	Application schedule	No. of panicles	Grain yield (kg ha^{-1})
Control	-	222	2.3
45 Kg neem cake coated urea	(1+0+0+0)	286	3.4
45 Kg neem cake coated urea	(1/4+0+1/2+1/4)	332	4.1
45 Kg neem cake coated urea + prilled urea	(2/3+0+0+1/3)	343	4.3
45 Kg prilled urea	(0+1/2+1/4+1/4)	305	3.7

Volatilization loss of nitrogen varies with fertilizer type and soil moisture levels. Generally, in waterlogged upland systems the total loss of ammonia is higher from ammonium sulphate than from urea, but the contrary is true under unsaturated situations (Bandyopadhyay & Sen, 1986). In upland rice systems, application of N after crop establishment reduces volatilization losses more than pre-planting application. Even the tall indica rice varieties responded well to a top dressing of 20 kg N ha^{-1} at panicle initiation stage in acid clay loamy soils of Eastern India (Mishra *et al.*, 1998).

Application of urea mud balls at the root zone and split application of urea have been suggested to minimize losses. Experiments conducted at Jorhat, Assam revealed that application of urea mud balls with 50% urea at sowing, 25% at tillering and 25% at panicle initiation resulted in higher nitrate reductase activity, grain yield and protein content compared to applying all urea at the time of sowing (Bhuyan & Borah, 1997).

Nitrogen transformation under continuous submergence and intermittent moisture regimes in relation to rice yield was studied by Chakraborty & Mandal (1990). The availability of NH_4-N was higher under continuous submergence but the opposite was observed for NO_3-N. The apparent N use efficiency was higher at low N levels under continuous submergence, but under intermittent conditions N use efficiency was higher under high N application levels.

Sharma *et al.* (1994) showed that ammonia volatilization losses increased with increasing exchangeable sodium levels. Losses were higher under flooded than under intermittent conditions. In high alkali soils, low response to N compared to normal soils is due to ammonia volatilization losses, up to 45% of the applied N (Singandhupe & Rajput, 1996). They also concluded that total N uptake with irrigation one day after draining was significantly higher (10%) than with irrigation six days after draining.

3.7.2 Phosphorus

Phosphorus (P) deficiencies occur in many soils such as Ultisols, Oxisols, Vertisols and certain Inceptisols. These soils are not only low in available P but they also fix P fertilizers. The increased P availability caused by soil submergence is still low in these soils. Phosphorus is often less deficient in flooded than in upland rice because more available forms of P are present in flooded soils. Padihar & Dikshit (1985) reported that increasing P application increased the phosphorus, sulphur and manganese content of the plant, but it decreased the iron content under submergence. Greater P uptake was recorded under alternate submergence and saturation conditions till maximum tillering. Continuous submergence resulted in considerable uptake (Dikshit & Padinar, 1988) at harvesting (Table 3.14).

Table 3.14. Phosphorous uptake by rice in pot experiments under different moisture regimes (Dikshit & Padihar, 1988).

Treatments	Phosphorous uptake (mg pot^{-1})	
	Maximum tillering	Harvesting
Continuous submergence	1.67	14.53
Alternate submergence and saturation	2.00	9.80
Continuous saturation	1.67	10.55
CD (p = 0.05)	NS	2.32

Recently, considerable research has been conducted aimed at alternative P sources for crop production in tropical soils. Results of experiments suggest that P uptake is improved with the application of green manure (Medhi & De Datta, 1997). Correlation analysis revealed a close correlation between P uptake and dry matter yield, and P uptake and grain yield.

Zaman *et al.* (1992) showed that P applications up to 26 kg ha^{-1} significantly increased grain yield regardless of the irrigation regime. Grain yield was higher with continuous flooding at all P levels. However, grain yield per unit water increased by 60% in the irrigation treatment with a water layer of 5 ±2 cm, 10 days after water was drained (Table 3.15).

Table 3.15. Effects of different moisture regimes and P fertilizer on rice yield and water use efficiency in the Indo-Gangetic plains (Zaman et al., 1992).

Moisture regime	Grain yield (t ha^{-1}) with different P application (kg ha^{-1})					Total water use (cm)	Water use efficiency (kg m^{-3})	
	0	13	26	37	Mean		0 kg P ha^{-1}	26 kg P ha^{-1}
Continuous submergence	4.5	5.0	5.4	5.5	5.1	92	48.9	58.7
Five days after draining water	4.2	4.7	5.0	5.1	4.7	62	67.7	80.6
Ten days after draining water	4.0	4.5	4.9	4.9	4.6	52	76.9	94.2
Mean	4.3	4.7	5.1	5.2	-	-	-	-

LSD values for P levels and moisture regimes are 0.1

3.7.3 Micronutrients

The uneven distribution of rainfall and water availability affects availability and loss of nutrients and, hence, affects the uptake by rice. Ponnamperuma (1964) showed an increase in concentration of micronutrients like Fe^{+2} and Mn^{+2} in the soil solution as a result of water-logging. Submerged rice soils showed a decline in available Zinc (Zn^{+2}) and copper (Cu^{+2}) content (Mandal *et al.*, 1992). Higher uptake of iron (Fe^{+2}) and manganese (Mn^{+2}) by rice is, therefore, expected under waterlogged conditions while a reverse trend in uptake of Zinc (Zn^{+2}) and copper (Cu^{+2}) has been found under moisture-deficient regimes.

Green manure significantly increases the availability of iron and its accumulation in rice compared to the control. It also increased the availability of manganese and copper in silty loam soils and their accumulation in rice (Bhattacharya & Mandal, 1996). Das & Mandal (1985) showed that application of

organic matter significantly increased Mn content in root, straw and grain, irrespective of moisture regimes and puddled and unpuddled conditions.

Incorporation of *Sesbania* green manure increases uptake of Fe^{+2} and Mn^{+2} but depresses uptake of Zn^{+2} and Cu^{+2} (Khinal *et al.*, 1987). However, a balanced uptake of micronutrients is expected under water-saving conditions combined with green manure application. Though availability of Fe^{+2} is reduced under water stress conditions, it could be improved by adjusting management practices, especially water.

The effect of soil moisture and lime application on growth and iron and manganese nutrition of rice in acid soils was reported by Verma & Tripathi (1981). The results revealed that iron and manganese contents in rice plants decreased after lime application to both saturated and submerged soils. In contrast, in upland conditions, on medium black soils in Western India, application of iron significantly reduced the antagonistic relationship between lime application and iron uptake (Mabulikar & Badhe, 1981).

Field experiments conducted at Nadia (West Bengal) in a silty loam soil revealed that moisture stress prior to submergence increased availability of iron and its uptake compared to continuous submergence. Early moisture stress prior to submergence also increased manganese availability but manganese uptake in rice was higher in the late stress situation. Moisture stress neither significantly affected the availability or uptake of zinc and copper.

3.8 Efficient water management

Traditional deep submergence of more than 10 cm depth causes great percolation losses due to higher hydraulic head and leads to excessive leaching losses of mobile nutrients. Improper water management reduced rice yields by 60% in different parts of the country. For example, rice productivity in Eastern India is lower (1.5-2.0 t ha^{-1}) than in North Western India (4.5-5 t ha^{-1}) due to a variety of reasons including an inefficient utilization of water resources. The Eastern part of India is the largest rice growing region (24.3 million ha), producing 60% of the national rice production. One of the major reasons for low productivity may be that about 80% of the rice area in this region exists of high-risk rainfed ecosystems.

Depending on soil type and prevailing weather conditions, irrigation at 1 to 4 days after draining of water resulted in rice yields comparable to yields realized under continuous submergence (Table 3.16). Similarly, in a sandy loam soil of Bihar, irrigation based on 3, 5 and 7 days drying after draining of water had similar effects on yield (Pradeep *et al.*, 1994).

Irrigation at booting and flowering stages increased yields by 20% (Table 3.17). Best results are obtained when timely supplemental irrigation is given only when dry spells occur during critical stages (Angadi, 1996).

Table 3.16. Effect of various irrigation practices on rice yields at different places in India (Sharma & Rajput, 1990).

Drainage period (days)	Cuttack (Rabi)[1]	Chipuma (Rabi)[1]	Kharaspur (Kharif)[2]	Kharaspur (Kharif)[2]	Faizabad (Kharif)[2]
Continuous submergence	4.37	7.21	4.49	5.81	2.98
Irrigation 1 DAWD	4.36	6.60	3.98	5.52	2.91
Irrigation 2 DAWD	4.35	6.47	3.89	5.50	2.48
Irrigation 4 DAWD	4.18	5.88	3.50	-	2.12

DAWD = Days After Water Drained
[1,2] Rabi = second rice season (October-January); Kharif = first rice season (June-September)

Table 3.17. Grain yield of rainfed rice as influenced by supplemental irrigation management (Angadi, 1996).

Treatment	Grain yield (t ha^{-1})			Percentage increase compared to rainfed
	1992	1994	Mean	
Rainfed	3.8	5.4	4.6	-
Irrigation at booting	5.3	5.4	5.4	17
Irrigation at flowering	4.4	4.9	4.7	1
Irrigation at grain filling	3.9	5.6	4.8	3
Irrigation at booting and flowering	5.4	5.7	5.5	20
Irrigation at flowering and grain filling	4.2	5.9	5.0	9
Irrigation at booting and grain filling	5.4	5.0	5.2	16
Irrigation at booting, flowering and grain filling	5.5	5.2	5.3	16
Daily irrigation from booting up to 10 days before harvest	5.2	5.3	5.3	14
LSD (p = 0.05)	1.3	NS	-	-

Water depth applied at each irrigation: 5 cm; NS = not significant

3.9 Weed management

As direct seeding of rice is the only possible method of sowing in uplands, weeds are efficient competitors and sometimes cause complete crop failure. About 40 to 85% of crop yield losses are caused by weeds. The major constraints in upland rice systems include:

a) weed competition,
b) nutrient losses due to light textured soils,
c) inadequate crop stand,
d) poor growth due to low input use,
e) occasional drought, and
f) pest and diseases, besides poor economic situation of the farmers.

Besides the type of crop, land preparation and cultural practices, weed control methods cause changes in weed population. In a water-saving rice eco-system, weeds compete with rice plants for light, nutrient and moisture resulting in a reduction of grain yield up to 80% (Sinha Babu *et al.*, 1992; Behera & Jha, 1992). Manual weeding of upland rice fields is not feasible. The traditional hand weeding practice needs to be substituted by herbicides to control weeds.

The critical period of weed competition for rice is up to 40 days after sowing, whereas Ali & Sankaran (1984) reported a period up to 60 days after sowing. The reason for this variation in critical period is due to variation in crop growth rate.

A pre-sowing sand mix application of pendimethalin at 1.0 kg ha^{-1} realized significantly greater rice dry matter production and productive tillers. Ramamoorthy & Mohamed (1992) reported promising results with application of pendimethalin in upland rice, i.e. no biomass and yield loss were measured. The maximum grain yield was obtained in a weed-free control (5.98 t ha^{-1}) which was comparable with the pre-emergence application of a thiobencarb and 2,4-DEE mixture at 1 and 0.5 kg ha^{-1}, respectively (Table 3.18), followed by one hand weeding operation after sowing.

Table 3.18. Yield of rice as influenced by different weed management practices.

Treatments	Grain yield (kg ha^{-1})
Farmers practice – control	1002
Hand weeding twice at 10-14 and 25 days after germination (DAG)	4101
Country plough at 15 DAG + 1 hand weeding 10 days after first weeding	4441
Pre-emergence herbicide Butachlor at 1.25 kg ai ha^{-1}	3267
Pre-emergence Thiobencarb at 1.25 kg a.i ha^{-1}	2886
CD (p = 0.05)	0.331

Viable weed management practices have also been designed for upland rice systems based on intercropping. Hand weeding and chemical weeding prevented the yield loss of cropping system by 48 and 44%, respectively, compared to a control with weeds (Table 3.19). Hand weeding and Basalin (herbicide) also increased the Land Equivalent Ratio (LER) by 85 and 74%, respectively, compared to no-weeding (Patra *et al.*, 1998).

Table 3.19. Effect of weed control treatments on rice and soybean and LER (Patra et al., 1998).

Weed control methods	Yield (kg ha^{-1})		Land Equivalent Ratio (LER)
	Rice	Soybean	
Control with weeds	1036	1141	0.62
Hand weeding	1991	2088	1.15
Herbicide (Basalin)	1839	1900	1.08
CD (p = 0.05)	244	216	0.08

Cowpea-rice intercropping showed weed suppression due to smothering effect and reduced the number of hand weedings without significantly affecting rice yield (Rajsekhar & Gogoi, 1994).

3.10 Water harvesting

Central parts of India are dominated by deep black clay soils with low infiltration capacity and high rainfall (1500 mm) of which 95% falls during the rainy season resulting in 60% runoff. Water harvesting is practiced to recycle water for stabilizing crop productivity in upland rice. Under rainfed conditions water is harvested in two ways: (1) run off collection and recycling and (2) in-situ water

harvesting. The results of experiments on water harvesting methods showed that sunken beds surrounded by raised beds with 9.0 m width increased yield and total dry matter by 36 and 33%, respectively. Grain and straw yield of rainfed rice were also highest using beds of 10.5 m width due to more favorable soil moisture regime (Sengar *et al.*, 1982) (Table 3.20).

Table 3.20. Effect of sunken beds with different water harvesting width on total dry matter and grain yield of rice (Sengar et al., 1982).

Water Harvesting Width (WHW)	Grain yield (t ha^{-1})	Total dry matter (t ha^{-1})
7.5 m	2.0	3.4
9.0 m	2.2	3.9
10.5 m	2.0	3.8
Control	1.4	2.6
CD (p = 0.05)	0.1	0.1

Sustainable rice production can be achieved by converting 5 to 7% of the cultivated area into runoff water harvesting ponds (Paul, 1988). The stored water can be efficiently utilized for application of irrigation at critical stages such as flowering.

3.11 Crop intensification

3.11.1 Intercropping

Intercropping systems are an option to reduce the risk of crop failures in water-limited environments. Results of experiments in acid soils of Southern India showed that rice and blackgram (4:1 row ratio) was the most suitable intercropping system (Ramamoorthy *et al.*, 1997) (Table 3.21).

Intercropping of direct seeded upland rice with soybean allows the increase of soybean yields, without sacrificing rice yields. Weed problems in intercropping systems are different from mono-crop rice systems. Intercropped rice and soybean reduced the weed population and weed biomass by 41 and 63%, respectively, compared to mono-cropped rice. Intercropping of direct seeded upland rice with soybean, in 2:2 or 4:2 row arrangements, produced higher total yields (3.5 t ha^{-1}) than rice (2.9 t ha^{-1}), soybean (2.5 t ha^{-1}) (Table 3.22). Patra *et al.*, (1998) showed a yield advantage of intercropping up to 29% with Land Equivalent Ratios (LER) of 1.28 to 1.29.

Table 3.21. Effect of intercropping and row ratios on Leaf Area Index and yield of upland rice (Ramamoorthy et al., 1997).

Treatments	Leaf Area Index	Rice grain yield (t ha^{-1})
Rice + Blackgram (2:1)	4.11	2.86
Rice + Blackgram (3:1)	4.28	3.30
Rice + Blackgram (4:1)	4.43	4.20
Rice + Greengram (2:1)	3.84	2.25
Rice + Greengram (3:1)	3.92	2.43
Rice + Greengram (4:1)	4.06	3.00
Rice + Soybean (2:1)	3.95	2.34
Rice + Soybean (3:1)	4.17	2.47
Rice + Soybean (4:1)	4.22	3.27
Mono-crop rice	4.58	4.57
CD (p = 0.05)	0.10	0.15

Table 3.22. Effect of intercropping on weed population and dry weight 75 days after sowing, and crop yields (Patra et al., 1998).

Treatments	Weed population (No m $^{-2}$)	Weed dry weight (g m $^{-2}$)	Yield (kg ha^{-1})	
			Rice	Soybean
Sole rice	133	121.6	2870	-
Sole Soybean	114	104.3	-	2547
Rice + Soybean (2:2)	78	44.6	1606	1931
Rice + Soybean (4:2)	86	54.8	1914	1569
Rice+ Soybean (1:1)	100	68.4	751	1372
Rice+ Soybean (2:1)	123	87.3	959	1118
CD (p = 0.05)	13.0	12.3	289	370

3.11.2 Double cropping

In Eastern India, substantial parts of upland are mono-cropped rice systems. Possibilities exist to grow a second crop on residual soil moisture. Experiments on infertile sandy loam soils indicated that safflower (October-January) could be grown after rice (June-September). Safflower (*Carthomus tinctorius* L.) after rice gave the highest yield followed by tobacco and blackgram (*Vigna mungo* L.) (Moorthy & Jha, 1980) (Table 3.23).

Table 3.23. Yields of different rainfed upland systems.

Cropping system	Yield (t ha^{-1})		Total net return (Rs. ha^{-1})
	Main crop (rice or finger millet)	Rabi crops	
Rice – Safflower	3.24	0.947	3524
Rice – Niger	3.66	0.486	2128
Rice – Blackgram	3.66	0.612	2590
Rice – Tobacco	3.47	0.615	2713
Finger millet - Safflower	2.13	0.794	2380
Finger millet – Niger	2.03	0.337	637
Finger millet - Blackgram	2.11	0.511	1101
Finger millet - Tobacco	2.05	0.511	1335

Kharif = First season (June-September)
Rabi = Second season (October-January)

3.12 Soil management

Rice requires a water regime near soil saturation for optimum yield. However, it is not always possible to maintain such a water regime due to erratic rainfall, canal closures, tube-well failures etc. Hence, rice is often exposed to water stress for a given period. Water stress conditions are more prevalent in years with low rainfall or early ending of the monsoon. Water stress increases the percolation rate (45.5%) and reduces rice yields with 9.19 q ha^{-1} (Goel &Verma, 1994) compared to no water stress conditions. The results also revealed that soil amendments increase rice yields both with and without water stress conditions. Under water stress conditions yields were even higher than under ample water supply (Table 3.24).

Table 3.24. Effect of different types of soil amendments and water stress conditions on rice yields and percolation rates.

Treatments	Rice yield (t ha^{-1})		Percolation rate (mm d^{-1})	
	With water stress	Without water stress	With water stress	Without water stress
Control	5.59	6.51	12.5	8.58
Rice husk	6.19	6.88	11.7	7.48
Gypsum	6.47	7.05	10.8	7.90
Farm yard manure	6.97	7.27	8.8	6.4
Sesbania acculeata	7.22	7.45	7.6	5.7
Mean	6.49	7.03	10.3	7.2
CD (p = 0.05)				
Water stress	0.61	-	-	-
Amendments	0.35	-	-	-

The positive effect of amendments (i.e. Gypsum, FYM and *Sesbania acculeata*) on soil physical properties, especially on soil aggregation, persisted after rice. Therefore, succeeding wheat crops under these treatments yielded more than the control (Khind *et al.*, 1985).

Physical manipulation of light textured soils to an optimum bulk density or minimum tillage of such fields may increase rice yields (Sharma & Katoch, 1985) (Table 3.25). In a less than normal rainfall year, mulched rice plots gave 520 kg ha^{-1} higher yields than plots without mulch.

Table 3.25. Grain and straw yields of upland rice as influenced by various physical treatments (Sharma & Katoch, 1985).

Treatment	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})
Conventional	1.39	4.09
Minimum tillage	1.93	4.67
Compaction to achieve bulk density of 1.6 mg m^{-3}	1.96	5.10
Compaction to achieve bulk density of 1.8 mg m^{-3}	1.73	4.68
Embedding polythene strips in the inter row space	1.90	5.02
CD (p = 0.05)	3.0	NS

3.13 Irrigation potential and rice cultivation in Tamil Nadu

Tamil Nadu is the most Southern state of India and largely depends on agriculture. During the past two decades, the net area sown with rice has declined from 48 to 44% and the cropping intensity also has declined from 123.4% in 1974-75 to 121.4% in the late nineties due to an increase of non-agricultural land use. With respect to the irrigated area, the area cultivated under tank irrigation declined from 28 to 24% (Palanisami & Paramasivam, 2000).

The state's irrigation potential (per capita) is only about 0.08 ha compared to India's average of 0.17 ha. The per capita area sown is about 0.15 ha compared to India's average of 0.26 ha. Considering the different sources of irrigation, out of the total irrigated area of 2.88 million ha during late nineties, canal sources accounted for about 0.84 million ha, wells about 1.37 million ha and tanks about 0.67 million ha (Table 3.26).

Table 3.26. Land use and area irrigated by different water sources in Tamil Nadu (Palanisami & Paramasivam, 2000).

Land use	Area (million ha)
Total geographical area	13.0
Net area sown	5.79
Cropping intensity	121.1 %
Net irrigated area	2.88
Canal	0.84
Wells	1.37
Tanks	0.67
Gross irrigated area	3.59
Irrigation intensity	130.0 %
Potential water availability	4.74 million ha m

Water shortage has resulted in a reduction of the irrigated area. In the past, the cropping pattern, an important indicator of water availability, was mainly oriented towards food crops which accounted for 92% of the irrigated area in 1960-61 and declined to 80% after the mid-nineties.

Presently, the domestic and industrial use of water claims 15% of the total water resources (agricultural the remaining 85%) and this is expected to increase to 25% in the year 2025. The projected irrigated area will be 4.47 million ha and the corresponding water requirement will be 5.21 million ha m. The

supply-demand gap based on a growth rate of irrigated crops is 2.12 million ha m (44.7%) (Table 3.26). In Tamil Nadu, 70% of the irrigated area is under rice. Different measures are required to meet future water demands, for example: (1) better water management practices, (2) introduction of improved irrigation methods, (3) development of water harvesting techniques, (4) waste water utilization, (5) salt water utilization, (6) groundwater extraction and management, and (7) rehabilitation of irrigation tanks.

Any water saving technique in rice cultivation would be a most welcome improvement. If successful technologies like the System of Rice Intensification (SRI) could be adjusted to Tamil Nadu, it would be a breakthrough in efficient water utilization.

Table 3.27. Projected water demand and supply in 2025 for Tamil Nadu (Palanisami & Paramasivam, 2000).

	Quantity (million ha m)
Total water supply	4.74
Demand for non-agricultural purposes	1.65
Available for agricultural purposes	3.09
Demand for water for agricultural purposes	3.57 - 4.55*

* *based on different estimates*

The current recommendation for water management of irrigated rice is the application of 5 cm water after the soil surface is drained. However, most farmers maintain flooded field conditions ignoring possible water scarcity.

3.14 Preliminary evaluation of SRI Tamil Nadu

A pilot trial was conducted at Coimbatore (11° N 77° E; 427 m above mean sea level), the wetland farm of Tamil Nadu Agricultural University during 2000-2001 with rice cultivar CO43 (135 d duration). It included two methods of crop establishment (wet seeding of sprouted seeds and placement of 10-day-old seedlings) and five plant densities (12.5 x 12.5 cm; 25 x 12.5 cm; 25 x 25 cm; 50 x 25 cm; and 50 x 50 cm). Water management consisted of intermittent irrigation in which water was supplied only in the evening and excess water was drained the following day.

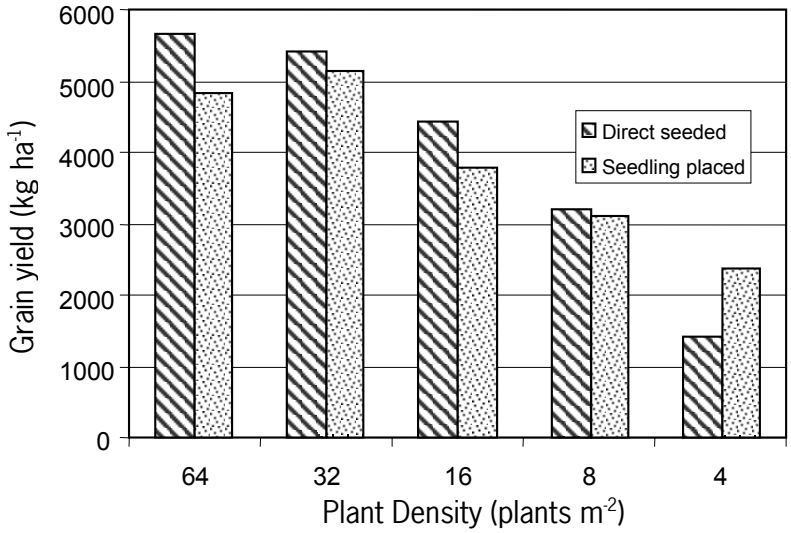


Figure 3.6. Grain yield of rice (CO43) with different plant densities and different seeding methods (direct seeded and seedling placement) under intermittent irrigation.

The results show that a plant density of 64 plants m^{-2} and 32 plants m^{-2} had significantly higher yields than plant densities of 16 plants m^{-2} or less. The grain yields recorded with 64 and 32 plants m^{-2} under intermittent irrigation produced yields comparable to yields realized under continuous flooded situations.

3.15 Conclusions

Traditional rice cultivation uses flood-water-management. Flood management requires various inputs, and is costly and time-consuming. In addition, it requires large quantities of water. Water tables in many rice growing regions in India are falling. Other priorities for water use (human, industrial or transportation), or lack of adequate water infrastructure may lead to restricted water use as a consequence of regulation. Possible consequences include increased production costs of rice or even prohibition of rice production in some regions.

Environmental concerns over water use are constantly debated. If rice can be produced using less water, then it will be less affected by these concerns. Many areas of the world grow non-flooded rice, often referred to as upland rice. These regions (Asia, Africa and South America) receive near adequate amounts of rainfall during the growing season.

The major biophysical constraints on the growth of rice yields in water-saving systems are drought, infertile soils, accelerated soil erosion, weeds and pest and diseases, and possible low nutrient use efficiency. The review of research on water-saving rice systems in India and related methods of cultivation (rainfed and irrigated uplands and lowlands with moisture stress) showed considerable scope for improvement of management and yield increase. Despite the problems in uplands, many of the upland trial results indicated yields comparable to yields in lowland submerged systems. Possibilities exist to grow irrigated/rainfed upland crops and rice as intercrops. Soil nutrient dynamics in space and time and crop intensification are the primary areas of research to explore water-saving rice production systems.

Yield reductions in water-saving rice production systems compared to conventional submerged rice systems can not be ruled out. However, more water use and related environmental problems are the

primary concern in submerged rice systems. Research efforts are required on genotype selection procedures, drought tolerance, nutrient dynamics and better weed control methods. Suitable agronomic management practices have to be developed to explore the viability of low water input systems in conventional and non-conventional rice areas. The new paradigm of research on water and rice should anticipate the potential water scarcity so that future food requirement can be met.

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4. Improving water-use efficiency for sustainable rice production systems

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Abstract

Since 1997, rice production and productivity no longer increase in many regions of Indonesia, threatening the future supply of rice for a rapidly growing population. Rice production and productivity, particularly in existing wetland rice ecosystems, have to be increased to meet future demands.

The growing scarcity of water in Indonesia has raised questions about the sustainability of rice production systems. Irrigated rice production is the greatest consumer of water and it is inefficient in the way it uses water.

No factor is more critical to rice production than water control. Although a lack of water is the primary constraint on high and stable rice yields, too much water is also a problem. Although water control is a major factor determining the feasibility of increasing rice production, soil and topographic conditions are also important. Soils with a low water holding capacity and fertility are difficult to manage without using great quantities of water. In such situations, organic matter amendments may improve soil conditions and increase water use efficiency. Sustainability of rice production system can only be maintained or improved by improving water-use efficiency.

4.1 Introduction

In recent years, worldwide, scarcity of and competition for water have been increasing. Opportunities for the development of new water resources for irrigation are limited. In many places, irrigated agriculture consumes more than two thirds of the available water. As the demand for industrial, municipal and other uses rises, less water will be available for agriculture. If food security is to be maintained, ways of increasing the productivity of water must be found (Barker *et al.*, 2000). Competition for water among agriculture, domestic use, and industry will focus greater attention on efficient water allocation and investment, and on increasing water use efficiency at the farm level (Pasandaran, 2000).

Agriculture holds a key position within Indonesian economy. Although it has been replaced as dominating foreign cash earner by oil, natural gas and timber, agriculture has remained, by far, the most important sector in terms of employment. In 1999, 43.21% of all households were active in the agricultural sector (CBS, 2000).

In Indonesia, as in most other Asian countries, rice is the primary food crop. In addition, rice production is important for national food security reasons and it has direct socio-economic importance. Rice self-sufficiency achieved in 1984 is no longer realised. It was only in a relatively short period that the Indonesian people proudly said: 'we are self-sufficient in rice'. Due to a high population growth rate, conversion of fertile soils from rice to other crops or non-agricultural activities, and problems in food distribution, rice production has declined to levels insufficient to meet self-sufficiency. In addition, prolonged drought in 1997 reduced Indonesian rice production by 3.37% from 51.1 million tons in 1996 while a national 'economic crisis' worsened the situation.

Some farmers, especially progressive and commercial farmers are aware that growing food crops only does not generate sufficient income to meet their needs. They have shifted their rice farming activities to other, more profitable crops such as shallot, garlic, citrus, and tobacco. Especially, agricultural production oriented at food crops are not very competitive and require high labour inputs (CRIFC, 1993). Because other sectors in urban areas provide more favorable income opportunities, labour forces abandon the agricultural sector.

Water, as the primary substance for living organism and an important factor in rice production systems, especially in lowlands, is no longer available without limitation. Water shortages, in particular due to weather variability, caused drought throughout the country, such as in 1991 and 1997. Water saving, water conservation, and increasing water use efficiency are currently major goals in agricultural development.

In lowland rice systems, producing about 94% of the national rice production, irrigation water is still spoiled. A large part of the irrigation water is lost through evaporation, seepage, and percolation. For lowland rice systems, innovative methods improving water use efficiency are urgently needed which can be easily implemented in farmers' field.

In rainfed areas, efforts to conserve water have already significantly contributed to increased production. However, in both lowland and rainfed rice areas, soil fertility is declining due to the intensive cultivation methods for decades. One of the options to maintain or improve soil fertility may be the incorporation of organic matter or application of mulch.

4.2 Experiences in the past

Strong commitment and well-implemented government policy through an action program have led to a substantial increase in food production in Indonesia. From the largest rice importing country in the world, Indonesia became self-sufficient for rice in 1984. Self-sufficiency was mainly realised through intensification of rice production. Three main factors have contributed to the intensification of rice production, i.e. irrigation, high yielding varieties, and fertilizers. Improved water availability contributed 16% to the increase in national rice production. Together with fertiliser and variety, it contributed 75% to national rice production (Abdurachman *et al.*, 2000). Improved water availability not only affected rice productivity, but also cropping intensity and the potential cropping area. High yielding and early maturing traits of new varieties allowed farmers to produce high yields and harvest more than one crop per year, particularly in irrigated lowland. In addition, new varieties are more resistant to major pests and diseases, and they require, therefore, fewer pesticides, which is important for reducing production costs, but also for environmental reasons (CRIFC, 1995).

KEPAS (1984) showed that, in addition to the productivity effects of intensification there are also environmental side effects, particularly due to the use of chemical inputs. The use of fertilisers and pesticides has greatly increased under the BIMAS (mass guidance) and INSUS (special intensification) programs. There are reports indicating that fertilizer application rates are well above recommended rates. There is a danger of contamination of sub-surface waters by fertilizers and other agro-chemicals, particularly by nitrates and pesticide compounds. During the last 15 years, national fertilizer consumption increased by 16% per year (CRIFC, 1995). Most of the fertilizer, about 70%, is applied in lowland rice. Data on fertilizer consumption and rice production indicate that efficiency of fertilizers is declining over time. The concern for reduced fertilizer efficiency is urgent since the government reduced fertilizer subsidies.

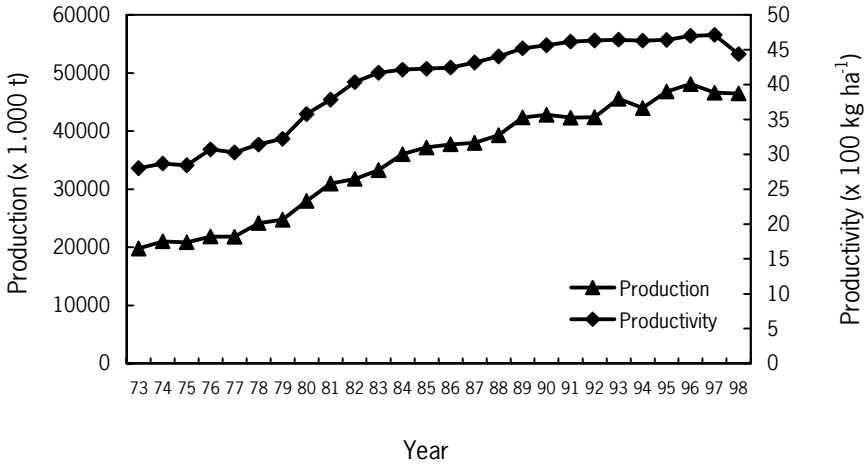

Figure 4.1. Lowland rice production and productivity in Indonesia, 1973–1998.

Lowland rice systems have always been important in Indonesia; 84 to 89% of the total harvested rice area came from lowland areas during 1973-1998 (Appendix 4.I) while these areas produced 92 to 95% of the national rice production (Appendix 4.II). Intensive rice production programs were particularly aimed at these areas. As a consequence of these efforts, Indonesia became selfsufficient in rice in 1984. Rice production and productivity stabilized since the 1990s (Fig. 4.1). Highest growth in lowland rice production and productivity was during 1978-1983 with more than 1.8 million ton y^{-1}, and yields increased by 206 kg ha^{-1} y^{-1}. During 1993-1998, lowland rice productivity decreased by 42 kg ha^{-1} y^{-1} (Table 4.1).

Table 4.1. Average lowland rice production and productivity changes in quinquennial periods in Indonesia during 1973-1998.

Period	Production change (t yr^{-1})	Productivity change (kg ha^{-1} yr^{-1})
1973-1978	873,200	67
1978-1983	1,824,380	206
1983-1988	1,204,340	56
1988-1993	1,238,560	48
1993-1998	184,780	- 42

Sources: Central Bureau of Statistics/CBS (1974-2000)

Rice intensification programs were started in 1959 (Kartaatmadja *et al.*, 2000), without much attention for maintenance or improvement of soil fertility. Declining production and productivity is partly caused by neglecting soil fertility issues.

Irrigated lowland rice is the major type of lowland rice production in Indonesia, i.e. 56.2 % of the total lowland rice area in 1997 was irrigated, while the rainfed lowland area was 2.12 million hectare (Table 4.2). Irrigated and rainfed ecosystems encompass 81.2 % of the total lowland rice area in Indonesia. Thus, major increase in rice production must come from irrigated and rainfed lowland rice ecosystems.

Table 4.2. Lowland rice areas under several rice production systems (ha) in Indonesia, 1997.

Island	Irrigated	Rainfed	Valley	Others	Total	% of total
Java	2,550,076	774,949	1,531	2,690	3,329,246	39.21
Sumatra	1,059,928	637,521	297,795	435,045	2,430,289	28.63
Bali & NT	329,424	61,655	31	6,520	397,630	4.68
Kalimantan	206,646	371,200	297,032	517,298	1,392,176	16.40
Sulawesi	624,566	278,392	3,123	34,622	940,703	11.48
Total	4,770,640	2,123,717	599,512	996,175	8,490,044	
% of total	56.19	25.01	7.06	11.73		

Sources: CBS (1999 a, b,c)

In rainfed areas, both lowland and upland, successful production is determined by the seasonal rainfall distribution pattern. According to CBS (1999a; 1999b), two rice crops per year are grown on 419,476 hectares of rainfed lowland area. In some parts of Indonesia farmers use a technique called *gogorancah,* which means that they make use of pre-monsoon rains with direct seeded rice, and leave the crop under upland conditions until enough rainfall has fallen to treat the crop as lowland rice. After harvesting the first crop, the second rice crop is planted with minimum tillage.

Upland rice is found under a wide range of climates, topography, and soil types, usually as subsistence crops with few purchased inputs, because upland farmers are among the poorest in Indonesia. Upland farmers experience many constraints in realising high yields, such as drought, diseases, acid soils low in phosphorus, and weeds. In 1997, the upland rice area was 1.26 million ha, producing 2.79 million ton, which is 5.64% of the national rice production. Productivity is low, 1.21-2.21 ton ha^{-1} during 1973-1998 (Appendices 4.I, 4.II, and 4.III). Drought, pests and diseases, as well as poor soil fertility status limit the adoption of improved varieties.

Constraints in rainfed areas are closely related to water availability. Statistics from 1995-1997show an increased area affected by drought damage (Table 4.3). The area affected by drought was 13,141 and 36,217 ha in 1995 and 1996, respectively. In 1997, drought damage increased further to 317,786 ha. The area of total crop failure due to drought also shows the severity of drought: 9,552 ha in 1995 compared to 147,073 ha in 1997. In contrast, the area damaged by floods decreased during 1995-1997.

Table 4.3. Flood and drought damages on rice crop areas (ha) in Indonesia, 1995-1997.

Damage caused by	1995	1996	1997
Damaged area:			
Flood	74,794	62,775	20,739
Drought	13,141	36,217	317,786
Crop failure by:			
Flood	38,520	37,105	10,896
Drought	9,552	19,524	147,073

Source: CBS (1996-1998)

4.3 Water use efficiency in rice production

4.3.1 Irrigated rice

Irrigated rice is a great and inefficient consumer of water, it requires about 5,000 litres of water to produce 1 kilogram of rice. Irrigation water is not (yet) efficiently applied. For example, water losses are relatively high along secondary canals, and they reduce the water flow entering tertiary plots. Such losses reduce the cropping area and equal water distribution. In addition, there is no systemic effort to increase water use efficiency in irrigated lowland rice cultivation.

In general, rice yields are proportional to the total amount of water transpired by the crop. The ratio of rice grain yield to transpiration is about 1:1000, i.e. to produce 1 kg rice, only 1 ton water is needed for transpiration. To produce 10 t rice ha^{-1}, 1000 mm rainfall is required if no losses occur and all the water is used for transpiration (Setter *et al.*, 1995). Unfortunately, much water is lost as evaporation.

Based on their own knowledge and experience, local farmers developed measures to use water more efficiently. Water savings are often used for other purposes than rice cultivation, e.g. fish cultivation. Farmers produce fish in the same field as the lowland rice crop (*mina-padi*; *mina* means fish and *padi* for rice), and especially when the price for fish is high, a part of the irrigation water is 'sacrificed' for *ikan air-deras,* in which fishes in cages are produced in a water stream.

Rice-fish cultivation combines rice and fish production in lowland rice fields, to increase farm income. The technique has many advantages. For instance, rice monoculture requires two weedings, compared to one weeding needed for rice-fish cultivation. Insecticide use is also lower because the recommended fish type feeds on several insect species. This technique of rice-fish cultivation has been developed in 14 of the 27 provinces of Indonesia (CRIFC, 1995).

Experiments conducted in Sukamandi, during the dry the season (DS) of 1998 and wet season (WS) of 1998/1999 with direct seeding technology clearly indicated that flooding is not beneficial for the rice crop. In both seasons, different drainage treatments (less-water) produced significantly higher yields than the flooding treatment (Table 4.4). Intermittent irrigation saves water and enables to irrigate more rice fields without reducing rice yields. Flooding at only as high as soil surface for 36-85 days after transplanting can cut water use down to 40% with no reduction in rice yields (CRIFC, 1995).

Table 4.4. Yields of direct seeding lowland rice in different irrigation treatments. Sukamandi, dry season 1998 (DS 1998) and wet season (WS 1998/1999).

Irrigation treatment	Paddy yield (t ha^{-1})	
	DS 1998	WS 1998/1999
1. Flooding (Fd) 5-10 cm	5.83 b	5.30 b
2. Fd, drain at 45-55 DAS [a)]	6.74 a	5.90 a
3. Fd, drain at 40-60 DAS	7.04 a	6.21 a
4. Fd, no standing water at 20 DAS until harvest	6.73 a	6.13 a
5. Treatment 4, drain at 40-60 DAS	6.60 a	6.08 a

Values in columns followed by the same letter; are not significantly different at 5% DNMRT (Duncan's New Multiple Range Test).
a) DAS = Days After Seeding
Source: BALITPA (1999)

Recently, a new rice production system, specifically for irrigated lowland rice areas, has been developed and applied in 8 provinces of Indonesia. The system uses water more efficiently than flooding systems through intermittent irrigation. It could also improve the fertility of degraded soils and increases farm income. During the dry season of 1999, demonstration plots in Cianjur and Sukamandi yielded 6.3-6.8 t ha^{-1} while adjacent farmers produced 4.1-5.4 t ha^{-1}. In the wet season of 1999/2000, yields were even higher, i.e. 9.5 t ha^{-1} compared to 5.6-6.9 t ha^{-1} at farmers' fields. Farmers using this method in the wet season of 2000/2001 produced 7.34-8.46 t ha^{-1}.

4.3.2 Rainfed rice

Drought occurs when water deficit limits crop growth and yield. Drought occurs almost in all rainfed rice areas at some time during the growing season, and may also happen in irrigated rice areas when irrigation resources are insufficient to meet demand. Drought escape is the most important mechanism to assure stable and optimal yields in water-limited environments. The escape mechanism is based on a matching of growth duration with rainfall distribution so that the crop passes critical development stages without water limitations, especially the panicle emergence stage. Early- or late-maturing varieties may often be able to escape or recover from drought. Also by using *gogorancah* systems in rainfed lowland rice, crops can escape drought during the critical stage.

The use of water collector technology (*embung*) in rainfed rice systems is another method to overcome a limited water supply. An *embung* is a water reservoir (pond) from which water can be distributed to irrigate crops during dry periods. In addition, during wet periods, a farm pond may be used to produce fish. The optimum area to construct a pond is about 4-5% of the irrigated area. Farmers with ponds earn about 50% more than farmers without ponds (CRIFC, 1995). To prevent losses due to evaporation, seepage and percolation, ponds may be 3.75 m deep, the walls must be covered using plastic sheets and the surface must be covered by growing vines (Sasa & Mulyadi, 1999).

4.4 Potential for development

Indonesia is a group of islands with a population of 206 million (1999). The country is about 5,000 km long from the northern tip of Sumatra island in the west to Irian Jaya in the east. Out of more than 13,600 islands that stretch along the equator, there are five of world's largest islands: Kalimantan, Sumatra, Irian Jaya, Sulawesi, and Java besides the world's famous island of Bali and the 'spice islands' of Maluku (Moluccas). Java, which covers only 6.63% of Indonesia's total area, supports about 58.68% of the population (CBS, 2000). It has the most fertile soils and produces most of the country's agricultural and industrial outputs. About 8.5 million hectare of agricultural land is lowland suitable for rice cultivation of which 53% receives irrigation.

Agriculture plays an important role as provider of food, foreign exchange and employment. It also contributes to the development of other sectors, such as by providing raw materials for industry. In 1985, agriculture absorbed 34 million or 54% of the total labour force; this percentage decreased to 43.21% (38.4 million) in 1999.

Indonesia's projected water availability based on rainfall, evaporation, runoff and depth of ground-water is estimated at 2,110 mm y^{-1}, or 127,775 m^3 s^{-1} (Pawitan *et al.*, 1996, Table 4.5).

Table 4.5. Rainfall and total available water in Indonesia.

Islands	Rainfall	Total available water	
	(mm yr^{-1})	(mm yr^{-1})	(m^3 s^{-1})
Sumatra	2,801	2,128	32,198
Java	2,555	1,915	7,360
Bali & Nusa Tenggara	1,695	1,167	3,251
Kalimantan	2,956	2,264	38,369
Sulawesi	2,156	1,568	9,458
Maluku	2,218	1,261	4,385
Irian Jaya	3,224	2,497	32,754
Indonesia	2,779	2,110	127,775

Source: Pawitan et al. (1996)

The harvested area of lowland rice in 1996 was 10,251,345 ha with a rice cropping intensity of 120% (Abdurachman *et al.*, 2000). In addition, the harvested area of irrigated lowland rice was 6,451,345 ha with an irrigated area of 4,772,121 ha, and thus a rice cropping intensity of 135%.

4.4.1 Irrigated rice

The irrigated lowland area has, by far, the highest potential area for increasing rice production, given irrigation water is used more efficiently. In the near future, the irrigated lowland area seems to have first priority for development, since water can be more efficiently used here. Of the total area in Indonesia, 2.42 million ha is potentially suitable for irrigation. Sumatra, Maluku and Irian Jaya, and Kalimantan have the largest potential areas: 0.73, 0.68, and 0.59 million ha, respectively (Table 4.6).

To compensate the loss of rice production because of prolonged drought in 1997, the AARD initiated a triple rice-cropping program called Rice Crop Intensity - 300 (RCI–300) covering a total area of 121,181 ha. Although rats and other vermin damaged 2,515 ha (2% of the total area), the total production was 544,776 tons with an average yield of 4.59 t ha^{-1} (Tim Teknis IP Padi-300 and SUP, 1999). The program indicates that intensive rice cropping is possible if water is available and crop and resources are managed properly. Adoption of RCI-300 could become an alternative to increase national rice production, particularly during food crises (Las *et al.*, 1999).

In the near future, double and triple rice cropping is likely to dominate in irrigated areas in Indonesia. Farmers growing five crops of rice in two years, the so-called RCI-250 program, can be found in West Java, Central Java, Yogyakarta, East Java, and in some parts of Bali and Lombok islands. Some earlier studies indicated that, in the long term, continuous and intensive rice monoculture in the lowland might reduce productivity. This could be caused by resource degradation (soil and water), pest build-up, and/or reduced resilience of the ecosystems. Nevertheless, intensification is likely to continue in irrigated areas, as population grows and food production needs to be increased.

Table 4.6. Existing irrigation areas in 1996, and potential area for irrigation development.

Islands	Existing irrigation area (ha)	Potential area for irrigation (ha)
Sumatra	874,320	730,695
Java	2,686,940	219,810
Bali & Nusa Tenggara	314,700	58,750
Kalimantan	187,820	594,855
Sulawesi	490,680	136,745
Maluku & Irian Jaya	11,970	675,320
Indonesia	4,566,430	2,416,175

Source: Abdurachman et al. (1999)

4.4.2 Rainfed rice

About 25% of lowland rice areas are rainfed. Rainfall and its distribution pattern vary greatly across location and over time. Therefore, an in-depth analysis is necessary to use rainfall efficiently. As described in the previous section, rainfall from surplus months can be conserved in ponds (embung), instead of losing it and causing erosion. Our knowledge about hydrological, physical, and socio-economic factors that determine successful operation of these ponds, however, is limited.

Damage to drought can also be avoided or reduced by using groundwater. Although it is not new, this technology is not yet well developed. A pump with a drilled pipe can be used to tap ground water while a hand tractor engine may power the pump. Groundwater pumping may also increase cropping intensity. Alternatively, it may exhaust ground water reserves and, therefore, it should be applied with care.

4.4.3 Organic fertilizer

Organic and green manure help to improve the soil's physical, chemical and microbiological conditions (Hesse, 1984). Different types of green manure such as azolla, rice straw, and animal manure, show positive effects on yield. Clarifying and quantifying the beneficial effect of organic matter, especially in rice production systems, need more fundamental and practical research. Fresh organic materials are relatively low in available nutrients, and pre-treatment, such as composting, can give better crop response depending upon the degree of decomposition of the organic matter, as well as upon its initial nutrient contents. On dryland soils, fresh organic matter can be used as mulch, and thus may contribute to improve water conservation after incorporation.

4.4.4 High yielding cultivars

Since 1987, a number of high yielding varieties have been released in Indonesia. Most of them were bred by CRIFC, some by IRRI and one by the Indonesian Agency for Atomic Energy. They are most suitable either for upland, lowland, or tidal swamps. Farmers' preference is related to high yield, taste (locally specific), early maturity, plant type and height, and resistance to major pests and diseases. Some improved rice varieties released from 1987 to 1995 are given in Appendix 4.IV. In addition, Ismail *et al.* (1999) identified three lines of *gogorancah* with good adaptation to water stress conditions in rainfed area of Jakenan, i.e. IR68833-2Jn-1, IR68836-52Jn and S3376e-Kn-5e.

4.5 Program and future strategy

The Agency for Agricultural Research and Development (AARD), responsible for research on agricultural development, has changed its research strategies towards more emphasis on water use efficiency, integrated resources management, and soil conservation for sustainable production systems. As one of the institutes under the AARD, the Research Institute for Rice (RIR) in Sukamandi was assigned the responsibility for rice research, i.e. to carry out research in rice production systems throughout Indonesia, aimed at attaining 'sustainable rice self-sufficiency'. Implementation of the programs is conducted in co-operation with the Assessment Institute for Agricultural Technology (AIAT) in each province.

All AARD working units are challenged to design productivity enhancing innovations. This strategy is especially important during the present economic crisis, in which the agricultural sector is expected to play a significant role in revitalising economic growth. At the moment, there are no systematic ways of saving water, as well as maintaining soil fertility, particularly in intensive irrigated lowland rice ecosystems.

To re-attain self-sufficiency in rice, different approaches should be introduced into research and development actions. According to Conway (1986), the next phase of agricultural development requires a radically different approach, one that is holistic and takes into account the complexities of agro-ecological and socio-economic processes.

To cope with the current problems in irrigated rice systems, the strategy is focused on water use efficiency, environmental conservation, and farmers' income. Implementation of this strategy is being operationalized through development and evaluation of integrated crop and resources management principles in certain irrigated rice areas.

4.5.1 Water-saving rice

Research on water-saving rice systems is increasing (Kartaatmadja *et al.*, 1999; Rubenandrasana, 1999; Uphoff, 1999). In fact, rice is not an aquatic plant but has aerenchimatous tissue 'to adapt' under flooded conditions. Research results showed that flooding is not the best condition to produce rice. It seems likely that water-less systems are able to increase rice production, as well as conserve water, particularly in irrigated lowland rice systems.

The improvement of water use efficiency through water-saving rice technology is under investigation and evaluated in 8 provinces in Indonesia. Hopefully, farmers in irrigated lowland areas will rapidly adopt this method of rice intensification using participatory approaches.

4.5.2 Integration

One important lesson from the current economic crisis is that Indonesia has to rely on her domestic capacity and resources to produce food. Rice self-sufficiency is not sustainable through subsidised and politically driven technologies, but only by production technologies integrating crop and resources management. Past experiences showed that the implementation of integrated pest management, weed management, and nutrient management were not enough to realise sustainable rice production systems. For this reason, integrated approaches should be broadened to all levels of production components, including socio-economic conditions.

4.5.3 Participatory development

One of the important factors contributing to the slow-down of technology development in rice cropping is the weak co-operation between research and extension. The co-operation should consider farmers as the central focus of development.

There is no doubt about the inefficient use of new technologies and research findings. There are hundreds, even thousands of research findings and recommendations published in scientific journals that gather dust on the shelves. Perhaps, they are not useless, but those useful ideas are not put to use. Also the time lag between discovery of new technologies or farming practices and adoption in farmers' field is usually long. In general, two to twenty years or more are needed for new technologies to be adopted at the farm level (Bernardo, 1987).

Farmers are not foolish; they do not simply adopt a recommended technology, but consider the risks involved with applying new technologies. They are wise enough to judge the suitability of a recommended technology. Singh (1984) has pointed out that the low level of adoption of recommended technologies can be attributed to the inappropriateness of technologies, ignorance or lack of skills, inability due to lack of resources, and unwillingness or lack of motivation. In addition, the FAO Expert Consultation on Linkages of Agricultural Extension with Research and Agricultural Education held in Bangkok on October 21-23, 1985 recognised weaknesses in research-extension programs (Bernardo, 1987).

A participatory approach is a bottom-up policy in agricultural development. Its emphasis is rather on facilitation through the use of participatory methodologies and less on inversion of capital and transfer of technology. According to Umans (1998), the participatory methodology is a set of practical tools which enables farmers to better assess their own problems and develop their own action plans. The farmers are no longer targets or beneficiaries but rather knowledgeable subjects of their own development, empowered by assisting agencies.

4.5.4 Synergy

Synergy is the positive interaction among factors or components. For example, the rhizosphere represents a system of interactions among root, soil (with its components: water, nutrients, air, and microbes), and human interventions. Components of this system interact and enable the system to operate appropriately, soundly, and sustainable. Knowledge about the synergies among components contributes to managing the rhizosphere in a sustainable and more productive way. Water-saving rice technology will create a more aerobe and healthier soil environment supporting better root growth and distribution which, in turn, feed and support a more vigorous plant.

4.5.5 Research programs

Research in irrigated rice production systems focuses on improving water use efficiency, i.e. water conservation and decreasing water consumption such as intermittent irrigation and rice varieties adapted to the systems with less water. Issues that should get priority include:

- Identification of varieties adapted to drought and intermittent irrigation.
- Root characteristics in relation to organic matter application in 'semi-irrigated' rice systems.
- Role of organic matter in improving water use efficiency and soil fertility, as well as increasing rice yield.

Research programs on water and rice cannot be separated from other relevant factors since almost all cultivation measures are, directly or indirectly, related to water availability. Changing moisture

availability during plant growth affects the availability of soil nutrients, as well as basic physiological processes. Research programs in rice production system will be concentrated on water use efficiency, improvement of soil fertility through organic matter application, and issues related to changing moisture regimes in rice ecosystems.

4.6 Conclusion

Concern over water scarcity is rising in Indonesia. Prolonged dry periods in 1991, 1994 and 1997, and associated water shortages have raised questions about the sustainability of the 'conventional' system of rice production. Major changes in practices, policies and institutions will be required to ensure that limited water resources are appropriately managed to increase the productivity of water in irrigated agriculture. If these steps are not taken, rice will be the crop most affected, as it depends heavily on irrigation. Rice is and will always be an important food crop in the world, especially in Asia. For future development of rice production, particularly in Indonesia, efficiency of irrigation will be very important.

Because production and productivity are stabilising and soil degradation is increasing, new technologies are required to continue exploiting rice ecosystems in intensive ways, even in higher intensities (3 crops per year) than currently practiced. It is the responsibility of the AARD and its institutions to find new methods of intensification of rice ecosystems. We have to change our strategy, methodology, and approaches to support our farmers in raising yields in a sustainable way, e.g. with less water. It is not too late to implement new policies to change the way of rice production and to protect resources and rice production. Unfortunately, the green revolution has run out of steam. The returns to varieties and inputs on which the revolution was primarily based, have diminished. A high yield plateau has been realised, but high oil prices make critical inputs costly, such as fertilizers, pesticides and other agricultural inputs. In addition, water scarcity threatens such rice production systems. Agricultural research and development in the future, especially in rice production systems, should aim at increasing yield and farmers' income, as well as maintaining/improving soil fertility under the boundary conditions of using less water. To achieve these goals, new approaches should be followed, i.e. development of water-less-rice systems based on integration, participation, and synergy.

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Appendix 4-I.

Lowland and upland rice harvested areas in Indonesia, 1973-1998

Year	Harvested area (x 1000 ha)			
	Lowland rice	Upland rice	Total	% lowland of total
1973	7,063.6	1,340.0	8,403.6	84.05
1974	7,340.2	1,168.4	8,508.6	86.27
1975	7,334.5	1,160.6	8,495.1	86.34
1976	7,229.4	1,139.3	8,368.7	86.39
1977	7,202.4	1,157.2	8,359.6	86.17
1978	7,698.4	1,230.8	8,929.2	86.22
1979	7,675.1	1,128.4	8,803.6	87.18
1980	7,824.0	1,181.0	9,005.1	86.88
1981	8,191.0	1,190.8	9,381.8	87.31
1982	7,872.6	1,115.8	8,988.4	87.59
1983	7,986.9	1,175.6	9,162.5	87.17
1984	8,547.1	1,216.5	9,763.6	87.54
1985	8,755.7	1,146.6	9,902.2	88.42
1986	8,888.0	1,100.4	9,988.5	88.98
1987	8,796.3	1,126.3	9,922.6	88.65
1988	8,925.4	1,212.8	10,138.2	88.04
1989	9,374.9	1,156.3	10,531.2	89.02
1990	9,377.5	1,124.9	10,502.4	98.29
1991	9,168.5	1,113.0	10,281.5	89.17
1992	9,799.1	1,304.2	11,103.3	88.25
1993	9,806.9	1,205.9	11,012.8	89.05
1994	9,494.0	1,239.8	10,733.8	88.45
1995	10,081.2	1,357.5	11,438.8	88.13
1996	10,251.4	1,318.3	11,569.7	88.61
1997	9,881.8	1,258.8	11,140.6	88.70
1998	10,475.6	1,254.8	11,730.3	88.30

Sources: Central Bureau of Statistics

Appendix 4-II.
Lowland and upland rice production in Indonesia, 1973-1998

Year	Production (x 1000 ton)			
	Lowland rice	Upland rice	Total	% lowland of total
1973	19,807.3	1,674.0	21,481.3	92.21
1974	21,052.9	1,411.5	22,464.4	93.72
1975	20,849.8	1,480.8	22,330.6	93.37
1976	21,851.5	1,449.4	23,300.9	93.78
1977	21,808.3	1,538.8	23,347.1	93.41
1978	24,172.4	1,599.2	25,771.6	93.79
1979	24,731.9	1,550.8	26,282.7	94.10
1980	27,993.1	1,658.8	29,651.9	94.41
1981	30,988.8	1,785.4	32,774.2	94.55
1982	31,775.6	1,808.1	33,583.7	94.62
1983	33,294.3	2,008.8	35,303.1	93.31
1984	36,017.3	2,119.1	38,136.4	94.44
1985	37,207.4	2,005.5	39,032.9	94.86
1986	37,739.6	1,987.1	39,726.7	95.00
1987	37,969.6	2,108.6	40,078.2	94.74
1988	39,316.1	2,360.1	41,676.2	94.34
1989	42,371.3	2,354.3	44,725.6	94.74
1990	42,825.3	2,353.5	45,178.8	94.79
1991	42,330.9	2,357.3	44,688.2	94.73
1992	42,413.6	2,826.4	45,240.0	93.75
1993	45,558.9	2,622.2	48,181.1	94.56
1994	43,959.2	2,682.3	46,641.5	94.25
1995	46,805.7	2,938.5	49,744.2	94.09
1996	48,118.3	2,913.2	51,101.5	94.30
1997	46,591.9	2,785.2	49,377.1	94.36
1998	46,482.8	2,753.9	49,236.7	94.41

Source: Central Bureau of Statistics

Appendix 4-III.

Lowland and upland rice productivity (x 100 kg ha^{-1}) in Indonesia, 1973-1998

Year	Lowland rice	Upland rice	Average
1973	28.04	12.49	25.56
1974	28.68	12.08	26.40
1975	28.43	12.76	26.29
1976	30.72	12.72	27.84
1977	30.28	13.30	27.93
1978	31.40	12.99	28.86
1979	32.22	13.74	29.85
1980	35.78	14.05	32.93
1981	37.83	14.99	34.93
1982	40.36	16.2	37.36
1983	41.69	17.09	38.53
1984	42.14	17.42	39.06
1985	42.29	17.49	39.42
1986	42.46	18.06	39.77
1987	43.17	18.72	40.39
1988	44.05	19.46	41.11
1989	45.20	20.36	42.47
1990	45.67	20.92	43.02
1991	46.17	21.18	43.46
1992	46.34	21.67	43.45
1993	46.46	21.74	43.75
1994	46.30	21.63	43.45
1995	46.43	21.65	43.49
1996	47.01	22.10	44.17
1997	47.15	22.13	44.32
1998	44.37	21.95	41.97

Source: Central Bureau of Statistics

Appendix 4-IV.
Improved rice varieties released in Indonesia from 1987 to 1995

Variety*	Yield** (ton ha^{-1})	Maturity (days)	Taste	Resistant***
Lowland, low elevation				
Dodokan ('87)	4-7	105	Good	BPH1,2,B,BLB
Jangkok ('87)	4-7	100	Good	BPH1,2,B,BLB
Ciliwung ('88)	5-8	121	Good	BPH1,2,GLH,T
Walanai ('89)	5-8	125	Medium	BPH1,BLB,BLS
Lusi ('89)	5-8	135	Glutinous	BPH1,2,BLB,BLS
Way Seputih ('89)	5-8	125	Good	BPH1,2,BLB
IR66 ('89)	5-8	115	Medium	BPH1,2,GLH,T
IR70 ('89)	5-8	130	Poor	BPH1,2,NS
IR72 ('89)	5-8	120	Poor	BPH1,2,NS
IR74 ('91)	5-7	115	Good	BPH1,2,GLH,WBP,B,BLB,T
Cenranae ('91)	5-8	115	Poor	BPH1,2,GLH,B,BLB,T
Lariang ('91)	5-8	115	Medium	BPH1,2,3,NS,BLB,T
Barumun ('91)	5-8	130	Good	BPH1,2,3,NS,BLB,T
Atomita 4 ('91)	5-8	120	Good	BPH1,2,BLB,BLS
Bengawan Solo ('93)	4.5-5.5	117	Good	BPH1,2,GLH,B,BLB,T
IR68 ('93)	5-6	125	Poor	BPH1,2,NS,T
Memberamo ('95)	6.1	115	Good	BPH1,2,3
Cibodas ('95)	6.3	123	Medium	BPH1,BLB
Lowland, high elevation				
Batang Sumani ('89)	5-8	140	Medium	B
Tidal Swamp				
Lematang ('91)	5-6	130	Poor	BPH1,2,NS,BS,Fe
Sei Lilin ('91)	5-6	125	Poor	BPH2,NS,Fe,BS
Upland				
Poso ('89)	3-5	120	Medium	BPH1,2,B,BLB
Laut Tawar ('89)	3-4	110	Medium	BPH1,2,B,BLB
Danau Tempe ('91)	3-5	135	Poor	B
Situgintung ('92)	2.0-3.5	140	Good	BPH1,2,B,BLB,
Gajah Mungkur ('94)	2-3	95	Medium	B,D
Kalimutu ('94)	2-3	95	Medium	B,D
Way Rarem ('94)	3-4	110	Poor	B,Fe,A1
Jatiluhur ('94)	2.5-3.5	105	Poor	B,S,SF

* *Figure in parentheses is year of release*

** *Range of dry grain yield. It depends on various factors such as soil fertility and cultural practices*

*** *BPH1,2,3,NS = brown planthopper biotype 1,2,3, North Sumatra*

GLH = green leafhopper *Al = aluminium toxicity* *B = blast*
Fe = iron toxicity *BLB = bacterial leaf blight* *D = drought*
BLS = bacterial leaf stripes *SF = seedling fly* *BS = brown spot*
S = shade *WBP = white-black planthopper* *T = tungro*

Source: CRIFC (1995)

5. Scientific issues raised by the system of rice intensification: a less-water rice cultivation system

Norman Uphoff (Cornell Institute for Food, Agriculture and Development, Ithaca, USA)

5.1 Introduction

The system of rice intensification (SRI) developed with farmers in Madagascar almost 20 years ago by Fr. Henri de Laulanié, and subsequently popularized there by the NGO, Association Tefy Saina (ATS), should be understood as a system of production that through synergistic interactions can produce much higher grain yields than usually achieved by conventional practices with new varieties and external inputs.

The combination of plant, soil, water and nutrient management practices that are used in SRI promotes: (a) measurably greater root growth, and (b) corresponding observable increases in tillering, with (c) resulting greater grain filling, and (d) often higher grain weight. Yields with SRI methods have been typically around 8 tons per hectare in Madagascar, where the national average is 2 tons (Hirsch, 2000). Similar yield increases have now been attained with SRI in half a dozen other countries, so this methodology does not work only in Madagascar.

That SRI requires only about half as much water as normally applied in irrigated rice production is of special concern for this collaborative project initiated by Wageningen researchers, though this opportunity needs more systematic and scientific investigation than undertaken so far. In Madagascar and now other countries, we find that in addition to higher productivity of water (yield per cubic meter), with SRI there is higher productivity of land (yield per hectare) and of labor (yield per person-day). This is achieved through more labor-intensive and management-intensive methods of cultivation.

Of special relevance to smaller and poorer farmers, SRI does not require purchased external inputs to obtain the highest yield. Compost is used instead of chemical fertilizer, and plant health and vigor usually keeps pest and disease levels below the threshold where use of pesticides and other agrochemicals is economically profitable. So the method is practically capital-saving, giving higher returns to whatever capital is used.

Because SRI demands less water and no agrochemicals, and methane emissions are reduced by keeping paddies unflooded, it is an environmentally-friendly method of agriculture, something uncommon. The high yields could be depleting soil nutrients, but so far we have not seen yield declines, and the soil and water management practices contribute to healthier soil by increasing soil organic matter and biological activity.

5.2 Water management

Tefy Saina and its partner, the Cornell International Institute for Food, Agriculture and Development (CIIFAD), have now had 6-12 years of experience with SRI that supports the claims made above. This paper therefore proceeds on the premise that the SRI methodology can and does in fact deliver on the claims made above. We are satisfied that this 'less-water' method of production offers many advantages, particularly for small and poor farmers who have relatively more labor than land, and little capital. Moreover, it has the advantage of being particularly relevant and accessible to small farmers,

who have access to only small amounts of land and little capital. A technology, which requires no purchased inputs and only greater investment of labor and skill, has more potential to contribute to equity than most agricultural technologies that have come along.

With SRI, a minimum of water is applied during the rice plants' growth, keeping the soil well-drained and reasonably aerated while meeting the plants' water requirements. During the reproductive phase that follows, a thin layer of water (1-3 cm) is kept standing on the field, though experiments may show that even this amount can be reduced advantageously. Because rice plants growing in submerged conditions form air pockets (aerenchyma) in their roots, it has been assumed that rice is an aquatic plant. This makes scientists and farmers reluctant to test how little water can be provided to lowland rice without compromising yield. Our experience suggests, however, that applying less water during the crop season will actually increase yield, though there are surely some limits to this proposition in terms of timing and amounts of water provided during the season.

Timing and control of water applications is essential for success with SRI, and these thus deserve critical and through evaluation. Puard and colleagues (1989) have shown that rice is not 'naturally' an aquatic plant. But their findings have received little attention. I would advance the following proposition, which is based on observations and various contributions in the literature:

Although rice can survive in saturated soil, it does not thrive under hypoxic conditions.

This proposition finds support from Hatta (1967) and Guerra *et al.* (1998), for example, and it appears that this view is now gaining some ground. The productivity of SRI methods is not explainable otherwise, and there are research findings such as those of Ramasamy *et al.* (1997) that support this conclusion. IRRI has begun to consider the possible advantages of 'aerobic rice', so this new thinking seems to be gaining acceptance. This research initiative by scientists at Wageningen University and Research Center with colleagues in a number of countries to evaluate 'less-water' rice production is the most ambitious effort so far to advance both scientific knowledge and farmers' practice in this regard.

5.3 What is SRI?

Most knowledge of SRI comes from Fr. De Laulanié who published only one article on SRI (1993). This was ignored because it seemed so fantastic and was not written in a stereotypically 'scientific' manner. A longer technical paper (1993a) in French has been translated into English and is available from CIIFAD. There are now a few published articles on SRI that go into some detail on the methodology and explanations for its effectiveness (Rabenandrasana, 1999; Uphoff, 1999).

Here a basic understanding of SRI methods is presented, as learned from Association Tefy Saina and from Malagasy farmers who have made this system work for them.

Land preparation is not done differently from regular irrigated rice cultivation, though leveling should be done carefully so that water can be applied very evenly.

1. Transplanting of very young seedlings, usually 8-12 days old and not more than 15 days old. This preserves a potential for tillering and rooting that is reduced if transplanting occurs after the 4th phyllochron, usually about 15 days after emergence. This date depends on temperature and other factors discussed by Nemoto *et al.* (1995).
2. Seedlings are transplanted singly and very carefully, to cause minimum trauma to the young plants. Roots are laid in the soil gently and horizontally rather than being plunged downward into the soil, which inverts the roots' tips. Transplanted seedlings with a J shape instead of an L shape will have their resumption of growth retarded.
3. Transplanting seedlings with wide spacing and in a square pattern, at least 25x25 cm and even wider, up to 50x50 cm, if soil and other conditions are supportive. This gives more room for both

root and canopy growth. It also facilitates mechanical hand weeding and consequent aeration of the soil.

4. The soil is kept moist but not inundated during the vegetative growth phase, so that the soil is aerated and never becomes hypoxic. Tefy Saina recommends putting a thin layer of water on the field at the end of the day, and draining off any remaining water in the morning. This exposes the field to the warmth of the sun during the day, absorbing rather than reflecting sun's radiation, and open to the air for both oxygen and nitrogen. Once roots are well established, irrigation can be skipped for 3-6 days at a time to stress the plant and encourage downward root growth. Fields are dried to the point of surface cracking, though not causing deep desiccation. In the reproductive phase, as noted above, 1-3 cm of water is kept continuously on the field so that water is continuously available to the plant. Fields are drained 25 days before harvest.
5. Early and frequent weeding is essential because otherwise weed growth will become a problem if fields are not covered with standing water. Weeding should start about 10 days after transplanting. Using a 'rotary hoe' that churns up the surface soil to remove weeds provides additional soil aeration, compared to hand weeding or use of herbicides. At least 2 weedings are necessary, but 3, 4 or even 5 are recommended, until the canopy closes so that weeding is no longer possible or necessary.

   We have some evidence that additional weedings, beyond 2, can increase yield by 1-2 tons per hectare per weeding, apparently because of soil aeration. This should be evaluated systematically. Soil aeration may contribute to greater biological nitrogen fixation by mixing aerobic and anaerobic soil horizons (Magdoff & Bouldin, 1970).
6. Although SRI was developed using chemical fertilizer, after subsidies were removed in the late 1980s, Fr. De Laulanié began using compost. This has advantages in terms of productivity if farmers are willing to invest the labor in this. Fertilizer will have beneficial results, but under many soil conditions, compost gives better results (see below).

SRI is a set of principles rather than a fixed technology or a package of practices. The original purpose of SRI as developed by Fr. De Laulanié was not simply to raise rice production, but to use these new methods with farmers to engage their intelligence and imagination, to uplift their thinking. This, indeed, is what the Malagasy term 'Tefy Saina' means in English.

Farmers are encouraged not just to learn specific practices but more important, to understand the principles of SRI and do their own experimenting and evaluation to fit the practices to their own conditions. These vary over short distances in Madagascar, as they do in most parts of the world. Only with adaptation can the very highest production be attained. As important, farmers' thinking becomes more vigorous and searching, leading to advances in both economy and culture.

5.3.1 Evidence of results

How do we know that these practices make a difference in how rice plants grow, which can explain the observed increases in yield?

1. Root growth can be massive in response to these practices. A pull test done by Joelibarison (1998) found that a clump of three rice plants grown under conventional conditions (mature seedlings, closely spaced, three per hill, grown in standing water) required an average of 28 kilograms of force to be pulled up. Single rice plants grown under SRI conditions (young seedling, widely spaced, one per hill, no standing water) required an average of 53 kilograms for uprooting. This is not as precise a test of root development as would be ideal, like measuring the surface area of a root system, but this is impossible, especially since most rice roots are hairlike. This method developed by IRRI (O'Toole & Soemartono, 1981; Ekanayake *et al.*, 1986) is a good proxy measure that reflects total root system development. Large disparities in resistance as seen in this comparison -- more than 5 times per plant -- clearly represent a significant difference in root development.

2. Tillering is greatly increased with these methods, by up to an order of magnitude. Thirty tillers per plant are fairly easy to achieve, and 50 tillers per plant are quite attainable. With really good use of SRI techniques, individual plants can have 100 fertile tillers or even more. This is because there has been no set-back in growth due to late transplanting (after the 4th phyllochron). Under ideal growing conditions, with no die-back of roots such as occurs when rice plants are grown under flooded conditions, the period of maximum tillering coincides with (rather than precedes) panicle initiation, as discussed below.
3. With SRI methods, we find grain filling to be positively associated with increased tillering rather than negative, as has been considered natural citing the law of diminishing returns -- more tiller per plant, fewer grains per tiller. However, instead of an inverse correlation between the number of fertile tillers per plant and the number of grains per panicle (e.g., Ying *et al.*, 1998), we observe with SRI practices a positive correlation. This helps to explain how yields can go from 2 tons to 8 tons per hectare, since such an increase would be impossible with a necessarily negative correlation. In fact, the negative correlations that have been observed are when rice is grown under flooded conditions, which produce massive root die-back (Kar *et al.*, 1974). He found that by the time of panicle initiation, 78% of the roots of rice plants being grown under flooded (hypoxic) conditions had degenerated, while control plants, grown in well-drained soil, had no such degeneration. This is known and accepted by scientists, who refer to this phenomenon as 'senescence.' This term unfortunately and incorrectly implies that the process is a natural and inevitable one. With SRI we observe a very different physiological outcome associated with the very different morphology of rice plants grown under these conditions.
4. Evidence of increased grain weight is still fragmentary, but various reports indicate a 10-15% increase in the number of grams per 1,000 grains. This is plausible given the more massive SRI root system that can access more nutrients in the soil and possibly support biological nitrogen fixation (BNF) in the rhizosphere. CARE/Bangladesh which has begun helping farmers participating in its IPM 'farmer field schools' use SRI reports a 15% increase in grain weight there (Aziz & Hasan, 2000).

The strategy of SRI, to summarize, is to promote (a) massive root growth, not considering roots as 'a waste' as do scientists who are fixated on maximizing 'harvest index', without considering that this is a 'closed-system' method of reasoning. With massive root systems, the rice plant is an open system. The nutrients devoted to root growth are not lost to the production system because they are partly available, after root decomposition, for the next crop.

This root system supports (b) greater tillering. Individual plants can have an order of magnitude more fertile tillers. Of course, one has to be concerned with the number of fertile tillers per square meter, not just per plant. But the greater tillering and grain filling with single plants widely spaced usually give more yield than plants grown more densely, with less root development.

The combination of more roots and tillers, which emerge and grow synchronously, supports (c) grain filling, with fewer sterile spikelets as a rule, and then (d) greater weight per grain. SRI is not something magic or mysterious. It capitalizes upon genetic and physiological potentials otherwise suppressed by conventional management practices. An additional benefit is that farmers in half a dozen countries have reported that with SRI practices, their rice plants are healthier and more vigorous and thus (e) less susceptible to damage by pests and diseases. This is something that needs systematic, scientific investigation, as farmers' accounts deserve to be taken seriously.

5.3.2 Evidence of synergy

As noted at the outset, the underlying explanation for this superior performance is not just the summation of positive practices and results, but their interaction. This makes evaluation more difficult, since most of our methods work more easily and surely in *ceteris paribus* analyses. However, it is not impossible -- just harder -- to take many factors into account simultaneously.

This is what is done in factorial trials. We are greatly indebted to Jean de Dieu Rajaonarison, and his advisor, Prof. Robert Randiamiharisoa, for undertaking such a difficult challenge during the summer (tsipala) season 2000 at the Centre de Baobab near Morandava on the west coast of Madagascar. Jean is writing up his research results in a thesis (memoire de fin d'etude) for the Faculty of Agriculture at the University of Antananarivo. What I am reporting here is just a preliminary analysis which shows in rough outline how synergy works among the SRI practices evaluated.

Because in factorial trials, one usually does at least three replications of each combination of factors, this is a huge undertaking, and we decided not to test all variables. Weeding was left untested, using the same weeding for all trials. Spacing was tested, but either unfortunately or fortunately, the values used (25x25 cm and 30x30 cm) were both within the SRI recommended range. Moreover, the average yield from the two sets of plots was identical (3.26 t ha^{-1}, with N = 144 in each set). So we have combined both sets of trials in the analysis that follows. This means that there are *six* replications of each combination of practices, rather than just three -- the common number, which increases the reliability of results being compared and evaluated.

The trials included rice variety as a factor, comparing the response of a high-yield variety (2798) and a traditional local variety (riz rouge). As will be seen, while the yield levels were different between the two varieties (and their response to compost vs. chemical fertilizer differed), basically they showed the same pattern of response and both demonstrated the hypothesized effect of synergy.
The SRI practices evaluated by comparison with contrasting conventional practices were:

1. **Age of seeding**: 8 days old vs. 16 days old
2. **Plants per hill**: 1 plant/hill vs. 3 plants/hill
3. **Water management**: aerated (well-drained) soil vs. saturated (flooded) soil
4. **Fertilization**: compost amendments vs. chemical fertilizer (16N/22P/11K)
   -- vs. no fertilization as a control.

The Morandava location was chosen because it normally has few pest and disease problems in the summer (*tsipala*, or minor) season, when there is no rain. Such problems need to be avoided in factorial trials if the effects of other production variables are to be correctly represented and assessed. Unfortunately, the soils in this area are very poor (*sable roux*), so yields are generally low, and they are even lower in this season. However, we were interested in *relative* yields rather than absolute levels.

Testing this number of factors required 96 plots (2x2x2x2x2x3), and three replications brought the number of plots to 288, all 2.5x2.5 m. There are fortunately a large number of farmers around the Centre who have been using SRI themselves and who could help with the labor and management of the plots. The results for each combination (six replications) are shown in Table 5.1, with the SRI combination (only one out of 24 combinations) in **bold face**. The full set of SRI practices produced 2.4 times more rice than conventional practices with the HYV, and 2.8 times more with the local variety (Table 5.2).

One can analyze these results in *ceteris paribus* terms to ascertain how much contribution each practice makes to the observed yields, other things being equal, i.e., when half of all the other practices are SRI and the other half are conventional, so that differences from all the other factors are in effect neutralized. It turns out, at least for these particular varieties and for these particular growing conditions, that planting young seedlings contributes most to yield -- 1.35 t ha^{-1}, other things being equal (Table 5.3). Careful water management, using a minimum of water and keeping soil well-drained and aerated, is the next most important factor, adding 0.85 t ha^{-1}, ceteris paribus. Planting single seedlings added 0.46 t ha^{-1} under these conditions, while using compost increased yield by 0.27 t ha^{-1} over what was obtained, on average, by applying NPK fertilizer. Both modes of fertilization gave greater yields on average than were obtained on plots with no fertilization. The latter yielded 2.19 t ha^{-1} on average (N = 96).

Considering just the set of trials with the high-yielding variety, we find that when only SRI practices were used (8-day seedlings, 1 per hill, in aerated soil, with compost), the yield was 6.83 t ha^{-1}. The HYV with conventional practices (16-day seedlings, 3 per hill, flooding, and NPK) produced 2.84 t ha^{-1}, a difference of almost 4 tons. Of this, 2.93 t ha^{-1} can be attributed to the sum of *ceteris paribus* differences noted above. The remaining difference, 1.06 t ha^{-1} (3.99-2.93), represents a difference due to synergistic or interaction effects.

For the traditional variety, a similar difference was attributable to such effects, 0.92 t ha^{-1}. Possibly inclusion of the weeding (surface soil aeration) factor or a significant difference in spacing between plants would add still more to yield differences and to the synergy; but that remains to be tested formally. Table 5.4 analyzes different levels of yield associated with SRI and non-SRI practices when there is no fertilization. It shows the same synergistic differences, or positive interaction effects.

These tables show consistently that while adding any one, two or three SRI practices have a beneficial effect on yield, whether including use of compost as an SRI practice or leaving out the fertilization factor. Considering both the HYV and traditional variety responses, we find that (under the conditions of the trials), moving from conventional practices to just one (any one) SRI practice, or from one to two practices, or from two to three practices can add on average about half a ton of yield -- 0.56 t ha^{-1}. However, moving to a full set of SRI practices adds almost three times as much -- 1.47 t ha^{-1} on average (Table 5.2 and 5.4 combined).

This same pattern of greater increments achieved when moving to a complete set of SRI practices is reflected in other dimensions of rice plant growth and performance: number of tillers, panicle length, grains per panicle, root depth, and root system development (resistance to uprooting). Adding a single SRI practice increased these values by 4.6% on average over values measured with no SRI practices. Adding a second SRI practice raised values another 6.8%; adding a third added another 10.3%; while going to all four SRI practices boosted values by an additional 21%!

Table 5.1. Factorial trial results comparing high-yielding and traditional variety yields (in t ha^{-1}) to SRI methods versus non-SRI methods.

	Continuous flooding				SRI water management			
	16-day seedlings		8-day seedlings		16-day seedlings		8-day seedlings	
	3 per hill	1 per hill	3 per hill	1 per hill	3 per hill	1 per hill	3 per hill	1 per hill
(a) Modern variety (2798 – riz blanc)								
No Fertilizer	1.68	1.90	2.28	2.31	1.69	1.92	2.61	3.47
NPK	2.84	2.79	4.08	4.50	4.04	4.10	5.75	6.62
Compost	2.69	2.73	3.35	3.85	4.18	3.82	4.42	**6.83**
(b) Traditional variety – riz rouge								
No Fertilizer	1.49	1.77	2.01	2.46	1.91	1.95	2.46	3.14
NPK	2.11	2.28	3.09	3.65	2.64	2.89	3.34	4.29
Compost	2.67	2.47	4.50	5.18	3.10	2.88	4.78	**5.96**

*Table 5.2. Factorial trial results, yield in tons ha^{-1}, evaluating effects of using greater numbers of SRI methods for different varieties (N of trials in parentheses; SRI practices shown in **bold face**).*

	HYV variety	Traditional variety	Average
Conventional			
SS/16/3/NPK	2.84 (6)	2.11 (6)	2.48 (12)
1 SRI Practice			
SS/ 16 / 3 / **C**	2.69 (6)	2.67 (6)	
SS/16/**1**/NPK	2.79 (6)	2.28 (6)	
SS/ **8** /3/NPK	4.08 (6)	3.09 (6)	
AS/16/3/NPK	4.04 (6)	2.64 (6)	
	3.39 (24)	2.67 (24)	3.03 (48)
	+ 0.55 t	+ 0.56t	+ 0.55 t
	(p = 0.021)	(p = 0.007)	
2 SRI Practices			
SS/16/ **1** / **C**	2.73 (6)	2.47 (6)	
SS / **8** / 3 / **C**	3.35 (6)	4.50 (6)	
AS/16/**1**/NPK	4.10 (6)	2.89 (6)	
AS/16/ 3 / **C**	4.18 (6)	3.10 (6)	
SS/ **8** /**1**/NPK	4.50 (6)	3.65 (6)	
AS/ **8** /3/NPK	5.75 (6)	3.34 (6)	
	4.10 (36)	3.27 (36)	3.69 (72)
	+ 0.71 t	+ 0.60 t	+ 0.66 t
	(p = 0.000)	(p = 0.000)	
3 SRI Practices			
SS/ **8** / **1** / **C**	3.85 (6)	5.18 (6)	
AS/16/ **1** / **C**	3.82 (6)	2.88 (6)	
AS/ **8** / 3 / **C**	4.42 (6)	4.78 (6)	
AS/ **8** /**1**/NPK	6.62 (6)	4.29 (6)	
	4.68 (24)	4.28 (24)	4.48 (48)
	+ 0.58 t	+ 0.99 t	+ 0.80 t
	(p = 0.000)	(p = 0.000)	
All SRI Practices			
AS / 8 / 1 / C	6.83 (6)	5.96 (6)	6.40 (12)
	+ 2.15 t	+ 1.68 t	+ 1.92 t
	(p = 0.000)	(p = 0.000)	

Table 5.3. Comparing yields of conventional and SRI practices under ceteris paribus conditions.

	Conventional practices (t ha^{-1})		SRI Practices (t ha^{-1})		Difference (t ha^{-1})	P
Seedling age (N = 144 each)	16 days old:	2.61	8 days old:	3.96	1.35	> 0.000
Water management (N = 144 each)	Flooded soil:	2.86	Aerated soil:	3.71	0.85	> 0.000
Plants/Hill (N = 144 each)	3 per hill:	3.05	1 per hill:	3.51	0.46	> 0.000
Fertilization (N = 96 each)	NPK added:	3.69	Compost:	3.96	0.27	> 0.008
			Total of differences = 2.93			

*Table 5.4. Factorial trial results, yield in t ha⁻¹, evaluating effects of SRI methods used without fertilization (N of trials in parentheses; SRI practices shown in **bold face**).*

	HYV variety	Traditional variety	Average
Conventional			
SS / 16 / 3	1.68 (6)	1.49 (6)	1.58 (12)
1 SRI Practice			
SS / 16 / **1**	1.90 (6)	1.77 (6)	
SS / **8** / 3	2.28 (6)	2.01 (6)	
AS / 16 / 3	1.69 (6)	1.91 (6)	
	1.96 (18)	1.89 (18)	1.93 (36)
	+ 0.28 t	+ 0.40 t	+ 0.35 t
	(p = 0.0036)	(p = 0.007)	
2 SRI Practices			
SS / **8** / **1**	2.31 (6)	2.46 (6)	
AS /16/ **1**	1.92 (6)	1.95 (6)	
AS / **8** / 3	2.61 (6)	2.46 (6)	
	2.28 (18)	2.28 (18)	2.28 (36)
	+ 0.32 t	+ 0.39 t	+ 0.35 t
	(p = 0.0003)	(p = 0.0003)	
All SRI Practices			
AS / 8 / 1	3.47 (6)	3.14 (6)	3.30 (12)
	+ 1.19 t	+ 0.86 t	+ 1.02 t
	(p = 0.000)	(p = 0.000)	

5.4 Implications for water-saving methodology

This factorial analysis will be repeated during 2001 under a different set of soil and climatic conditions on the high plateau in Madagascar. We invite other researchers to conduct similar factorial trials under still other conditions to see whether the hypothesis of synergy or positive interaction effects is confirmed. The relationships in the Morandava trials are so robust that we think they will be supported by further research, but it would be good to know what are the effects of different varieties, soils, climate, etc. on the magnitude of interaction effects.

SRI should be regarded as a 'package', though this word should not imply the kind of extension program which promotes a fixed set of practices. Rather one wants to take advantage of the synergy that Fr. de Laulanié was able to discover among management practices, applying the principles rather than taking prescribed actions, because one needs to vary spacing, water application, even age of transplanting, to local conditions.

The individual practices that make up SRI are each beneficial, but the real payoff comes from combining plant, soil, water and nutrient practices so that they collectively produce greater root development, tillering and grain filling. If farmers want to adopt just some of these practices, that is a step in the right direction. But they should be informed of the advantages of using the whole set of practices, having some explanations for why this synergy occurs. It should not be difficult to explain how and why more root growth occurs with combining wider spacing, younger plants and aerated soil, for example.

The good news for our water-saving concern is that there can be very substantial payoffs from using less water if these other practices are coupled with different water management, which reduces water applications during the growing season.

If indeed the returns to land and labor can be raised as well as the returns to water, this is a win-win-win situation. The usual constraints of 'tradeoffs' are relaxed by this positive-sum opportunity. There is a cost, to be sure: more labor investment is required during the season, and that can be a constraint for many rural households. And most of the world's rice paddies have been constructed so as to retain as much water as possible, not to be well-drained. So there will need to be some investment in irrigation infrastructure to attain the full potential of SRI methods.

To get the highest yields possible with SRI methods, where irrigation is provided in a field-to-field (cascade) distribution system, this should be replaced with delivery channels that serve individual fields, so farmers can control how much water they get on a daily basis. One might quite rationally sacrifice 5% of land area to obtain much higher yields, double or more, on the remaining 95%. Further, rice paddies should be leveled carefully, with in-field drainage systems created, so that farmers can keep their soil moist but never saturated.

All this requires a more intensive management orientation, not just planting and leaving fields, with a little attention to keeping fields flooded and reducing weeds and pests. Rather, one creates and then protects the soil, water and other conditions that give rice plants an optimum environment above and below ground for growth and grain production. Such conditions enable rice to express the genetic potential it has always had but which has been suppressed by close planting, hypoxic soil conditions, etc.

5.5 Scientific issues

SRI raises some interesting scientific questions that are related to this project but that go beyond it. In this section, I will identify some research issues that our project should consider, though we cannot tackle them all. My hope is that others will also join in this effort.

1. With SRI methods of rice cultivation, as reported already, the period of maximum tillering occurs concurrently with panicle initiation (PI), rather than preceding it, as reported in the literature. The latter condition certainly occurs, but it is attributable to the hypoxic growing conditions of flooded rice and to the die-back of roots noted above, rather than to some fixed consequence of genetic endowment. If growing rice in saturated soil has this profound effect on plant growth, this should be documented more clearly and its causal mechanisms clarified. Being able to show that flooded soil, which requires more water use during a season, impairs plant performance would give impetus to less application of water, whether or not reductions are linked to SRI practices. The research by Ramasamy *et al.* (1997) has made a good start in this direction.
2. Similarly, with SRI, we find a positive correlation between number of panicles per plant and number of grains per panicle (e.g., Bonlieu 1999). This should be examined by others to see whether this relationship holds up across a variety of conditions (with well-drained soil). The belief that there is *necessarily* a negative correlation is the premise for IRRI's efforts to breed a new 'super-rice' with minimum tillering but high grain filling (Khush & Peng, 1996). If the negative correlation observed is just a consequence of growing rice in flooded fields, this is important scientific information to have, as it will reorient thinking about how to create the most productive growing conditions for rice -- reinforcing a desire for water-saving.
3. The massive rice root growth under aerobic soil conditions measured by Joelibarison (1998) deserves more investigation. Does this also require other SRI practices (minimum transplanting trauma due to use of young plants and careful handling, plus wide spacing)? What are the effects of such root growth in terms of grain production and pest and disease resistance? Roots have been considered 'a waste' by many rice scientists. This view is due for reconsideration.

4. The uptake of N by irrigated rice plants is very 'inefficient', often in the range of only 20-30% (Cassman *et al.,* 1997). There is, however, reason to think that N uptake is a 'demand-driven' process, rather than one determined by supply. Kirk & Bouldin (1991) report that the uptake of N by rice roots is independent of the concentration of N at the roots' surface. This implies that the management of rice plants, and of the soil and water surrounding their roots, should seek to induce rapid growth that creates demand for N. Indeed, SRI management practices lead to rapid, even exponential increase in tillers and roots beyond the 8th phyllochron. Altered practices could reduce the need for N fertilizer applications and thereby improve groundwater quality (reducing nitrate pollution) as well as saving water.
5. If there is more demand for N with SRI practices, there must be supply to meet it if plant growth is to occur. Our experience with SRI suggests that there could be significant biological nitrogen fixation resulting from its plant, soil, water and nutrient management practices. Above we noted research some three decades old that found BNF was greatly increased when aerobic and anaerobic soil horizons were mixed (Magdoff & Bouldin, 1990). This occurs with SRI through the intermitting wetting and drying of soil and the use of a rotating hoe to churn up the top layers of soil in the field.

   Not much emphasis was placed on BNF previously because of inconclusive or inconsistent results. There was no need or incentive for in-depth search on this possibility as nutrient supply could be guaranteed by fertilizers. However, because of increasing environmental concerns and the degrading natural resource base, more attention should be paid to alternative fertilization with less environmental impact.

   Research by Döbereiner (1987) and her associates in Brazil (e.g., Baldani *et al.,* 1979; Boddy *et al.,* 1995) has laid a foundation for understanding BNF. Their finding that the history of N fertilizer use with both cultivars and soil has an effect on BNF (prior use of fertilizer with cultivars and/or soil inhibits BNF) has not been taken as seriously as it should be, in my view, though supported by research findings such as those of Van Berkum & Sloger (1983), which showed fertilizer suppressing production in the rhizosphere of nitrogenase, the enzyme that facilitates the BNF process.

   Knowledge in this area is limited partly because so little research has focused on soil biological processes. We do know that 80% of the bacteria in rice root zones are at least potentially N-fixing (Watanabe *et al.,* 1981). If using less water, together with other practices, can produce 'free' nitrogen for rice production, this is an opportunity that should be investigated, and exploited if its economics and ecology are viable.
6. Another question raised by SRI concerns plant nutrient requirements, at least what must be added to soil to ensure good growth. The soils where Tefy Saina and CIIFAD were introducing this method around Ranomafana National Park have been characterized as some of the poorest in the world (Johnson, 1994). It should not be possible to attain yields of 8 t ha^{-1} or higher, even double that, on soils which have been otherwise producing only 2 t ha^{-1}. Conventional wisdom says that compost or other organic inputs cannot boost yields because the plants growing on such poor soils will themselves have few nutrients to contribute back to the soil. This may be true, but the experience with SRI around Ranomafana should prompt soil scientists to investigate what is happening.

   Joelibarison is currently conducting field research in Madagascar for a Master's degree on Crop and Soil Sciences from Cornell looking at some of these issues. Possibly crop and soil scientists have overestimated plant nutrient requirements because their paradigm of plant growth is too mechanistic and reductionist, not capturing the biological element of nutrient uptake and utilization, where possibly very small amounts of nutrients can give very substantial growth results, particularly if they are well balanced and include sufficient micronutrients, not obtained when root systems are underdeveloped because of hypoxic growing conditions.

   This proposition may be considered radical for serious consideration, but there is some support for it in the literature. Primavesi (1984) found that maize plants could give 'normal' growth in hydroponic solutions as diluted as just 2% of 'normal' if their solutions were continually replenished, to maintain the low level of nutrients continuously. Root systems grew to 8 times

normal in order to be able to utilize the very small amounts of nutrients available. It is worth studying whether a different water management regime, together with different plant, soil and nutrient practices, can give good results without as great a supply of nutrients as now supposed.

7. Related to all the questions above, and central to our project, is the question of what constitutes an optimum water management/application system. Tefy Saina has developed some very empirical guidelines for water application, but these have not been evaluated scientifically. We have a Master's student in Agricultural and Biological Engineering, Oloro McHugh, currently conducting field research in Madagascar on this question under the supervision of Prof. Tammo Steenhuis at Cornell. This is just a first cut into this subject area. There will need to be many more detailed scientific studies after this initial work is done. We should know what is happening chemically in the soil and what is happening concurrently in physical and biological terms, when soils are wetted and then allowed to dry out. How wet and how dry should they become? For how long? How should applications be adjusted for optimal production from different kinds of soil? These questions can only be evaluated fully in conjunction with variations in other rice cultivation practices.
8. When rice fields are not kept flooded during the vegetative growth phase, this means that fields can absorb the sun's rays more fully, without any reflection. What are the effects of higher insolation and soil temperature on growth? Possibly there is little or no effect in the tropics or at low elevations but some effect in more temperate regions and at higher elevations. Scientists with whom I have discussed this issue so far have mostly discounted this factor as an influence on SRI performance. But it merits consideration, especially as a contributing factor to synergistic processes that have not been evaluated previously. By itself, soil warming might have little effect. If it is found that standing water lowers soil temperature and thus yield, compared to what is possible with SRI practices, this could create a very tangible incentive for water-saving. The effect may not be just one of temperature but also of soil aeration, both in terms of providing more oxygen in the rhizosphere to support biological activity, including BNF.
9. With massive root growth, as seen with SRI practices in well-drained soil, plants can avail themselves of a wider and better range of nutrients because their more amplified root system accesses a larger volume of soil. Perhaps this has an effect on the uptake of nutrients. Our colleague in Madagascar, Bruno Andrianaivo, who has worked on rice development for many years for the government's research agency FoFiFa, thinks rice scientists have been too fixated on nitrogen as a -- indeed the -- limiting factor. If SRI methods can promote BNF, as suggested above, then other nutrients like phosphorus, particularly deficient in Madagascar, become limiting. (Soil tests around Ranomafana have showed only 3-4 ppm of P in most locations - Johnson 1994.) More active microbial processes in the rhizosphere can alter pH and assist the uptake of P and other nutrients as solubilizers. Possibly there is some crucial micronutrient absorption going on, possibly through microbiological action, that boosts rice production with SRI. The research by Joelibarison may give some answers to this question, but this subject will warrant much additional research. Along with such research looking at effects on plant growth, there should be evaluation of any effects on pest and disease resistance.
10. One of the most interesting questions that our SRI experience has raised is whether there can be yield benefits from surface soil aeration. We have found that yields go up with the number of weedings done with the rotary hoe, by 1 ton or more per hectare for each additional weeding. In the 1997-98 season, 76 farmers around Ambatovaky used SRI practices, and we had quite good data on their production practices and results.
    - The 2 farmers who did no weedings with the mechanical hoe (only hand weeding) got almost 6 t ha^{-1}, more than a doubling of yield compared to standard practice, but lower than is attainable with SRI methods well used.
    - The 35 farmers who did 1 or 2 weedings, the minimum number recommended -- averaged about 7.5 t ha^{-1}.
    - The 24 farmers who did 3 weedings averaged 9.2 t ha^{-1}, a large increase over 1 or 2 weedings.
    - However, the 15 who were more ambitious and did 4 weedings got 11.7 t ha^{-1}.

Because a similar increase in yields was observed the season before with 40 farmers, we know this was not just a one-season phenomenon. Also, Bonlieu's thesis research on SRI (1999) showed average increases in yield associated with a larger number of weedings that aerated the soil. The labor cost of weeding a hectare of rice was only about $20-30, and the price received for a ton of rice was about $300, so this represented an incredibly high return to investment in labor. The capital cost of a mechanical hand weeder is only $10-20. This data set from Ambatovaky should justify some systematic investigation and evaluation of 'weeding' as a technique that does more than remove weeds. I think that it can raise yields by affecting beneficially the biological activity in soil when it is not maintained in a saturated condition.

11. A final, very technical but researchable issue that is suggested by the work of one of our project organizers, Hein ten Berge, with colleagues from India (Ramasamy *et al.* 1997), concerns the role of cytokinins, growth hormones regulating cell division in plants. The high yields with SRI methods are attributable in general terms to the shortened phyllochrons -- the greater number of growth cycles completed before anthesis -- which reflects an accelerated rate of cell division, or in colloquial terms, an accelerated 'biological clock.'.
    This only describes what is happening at a macro, observable level. What explains this? Probably there is some cytokinin activity that is affected by environmental conditions (Cockcroft *et al.*, 2000; Nemoto *et al.*, 1995). One possible causal pathway is that microorganisms in the rhizosphere such as yeast, under aerobic or alternating aerobic-anaerobic conditions, produce higher levels of CO_2. This is known to shorten the G1 phase in a particular grass (gramineae) species studied (*Dactylis*) and thereby to accelerate cell division and resulting plant growth. It occurred already to Ten Berge and associates as a plausible avenue for explanation. Along with larger-scale processes, the investigation of SRI should probably include cellular-level research.

The research questions posed above are already enough to occupy many researchers for several years. Not all will be priority questions for our work on SRI as a water-saving technology, but we should keep this broader set of issues in mind because SRI is quintessentially a holistic method for growing rice. Each part of the method has implications for other parts. Certainly the water-saving or water management aspects of SRI are not independent of the plant, soil and nutrient management practices; they are integrally related.

Accordingly, SRI presents a very promosing but thoroughly multidisciplinary challenge to researchers. It will be important for us to maintain very good communication across sub-projects as well as across disciplinary lines. Also, because SRI is far from what is usually done, observed and thought, we should keep our minds open to unconventional insights and conclusions. My hope is that SRI will greatly enrich and advance our understanding of agricultural science, in addition to producing more rice with less water.

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6. The present situation of water-saving rice cultivation and related research objectives in the Jiangxi province

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Abstract

Shortages of water resources are not only a global problem but are also an important constraint for agricultural development in China. In the past, research and application of water-saving rice cultivation was ignored in the southern part of China because of the high annual rainfall in this area. However, monthly rainfall is often not in equilibrium with agricultural water demand and frequently, water shortages occur in late season rice. Average food loss caused by drought in the Jiangxi province is about 583,900 t y^{-1}. At present, only few cultivation and management practices for water-saving rice cultivation exist. The latest developments in China on water saving techniques are discussed in this paper. Special attention is given to the growth of seedlings with less water and interval irrigation. These practices may not only save water but may also result in higher grain yields. Finally, research objectives for water-saving rice cultivation are discussed.

6.1 Introduction

Shortages of water resources are not only of global concern, but are also an important constraint for agricultural development in China. Average water availability is 2340 m^3 per capita in China, which is about one fourth of the average water availability in the world (Wang, 2000). Development of water-saving techniques in agriculture is one of the options to contribute to water shortage problems in China. In the northern part of China, research for water-saving rice cultivation has been conducted for almost 20 years, such as raising seedlings in dry nurseries and water management technology (Wang, 2000). Farmers have adopted some of these research results. Research on and application of water-saving rice cultivation was often neglected in the southern part of China because of the high annual rainfall in this area. However, monthly rainfall is often not in equilibrium with agricultural water demand and frequently, water shortages occur in late season rice. The latest developments on water saving techniques in China, i.e. raising seedlings with less water and using interval irrigation, are presented in this chapter.

6.2 General situation and drought damage in the Jiangxi province

6.2.1 Location and rainfall

Jiangxi province is located in the southeast of China, the low and middle part of Yangtze River basin, between $24^0$29 and $30^0$04 Northern latitude, and between $113^0$34 and $118^0$28 Eastern longitude. Annual rainfall varies between 1341 and 1939 mm. Rainfall from March to June comprises 55-60% of the total annual rainfall, 20% falls from July to September, and 20-25% from October to February.

6.2.2 Magnitude of drought damage

Jiangxi province is an agricultural province with rice as the main food crop. The area with rice (about 3 million ha) covers nearly 70% of the cultivated area. Rice can be grown during two seasons per year, early season rice grows from the middle of March to the middle of July and late season rice grows from the middle of June to the end of October (Fig. 6.1). In late season rice, water shortages may occur because rainfall is not sufficient to meet plant demand. In the last 50 years, the average area affected by drought was about 357,400 ha y^{-1} (Table 6.1) and average rice production loss was about 583,900 t y^{-1} (Table 6.2).

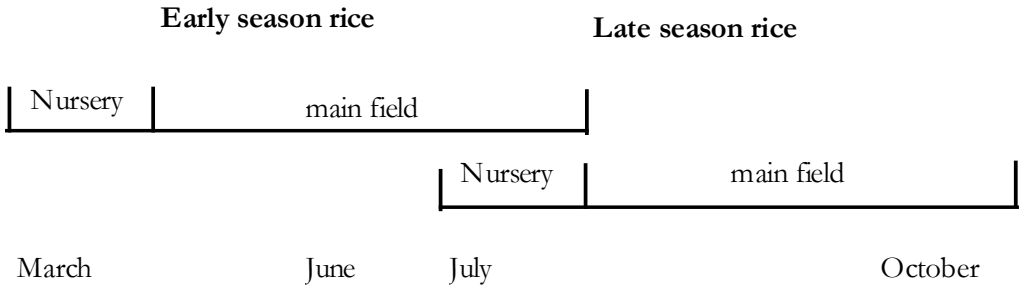

Figure 6.1. The growth stages of early and late season rice in the Jiangxi province.

Table 6.1. Average area annually affected by drought in the Jiangxi province in different periods (Huang, 2000).

Period	Average area of drought damage	
	Area (ha)	Percentage of cultivated area
1950-1959	397,000	14.60
1960-1969	311,000	11.74
1970-1979	262,800	10.91
1980-1989	412,000	17.35
1990-1998	404,100	17.43

Table 6.2. Average annual losses of rice production caused by drought in the Jiangxi province in different periods (Huang, 2000).

Period	Rice losses (t y^{-1})	Percentage of total annual production
1950-1959	706,000	12.0
1960-1969	488,000	7.01
1970-1979	481,000	4.41
1980-1989	725,000	4.85
1990	930,100	5.61

6.3 Present water saving technologies for rice cultivation in the Jiangxi province

6.3.1 Raising seedlings in dry nurseries

From a physiological viewpoint, rice seedlings are not well-adapted to grow under submerged conditions. The air space in the stem and root has not been formed completely before the fourth leaf develops (Diao, 1994). The root grows much better in an aerated nursery than in a submerged nursery (Fu, 1998). Seedling emergence rate is quite low, and seedling-floating rate and seedling mortality are very high in the traditional submerged nurseries. Dry nurseries can also save irrigation water since the nursery stage accounts for 25% of the total growth stage. Currently, two ways exist to raise seedlings in dry nurseries.

6.3.1.1 Dry nursery seedlings for transplanting

Seedlings are raised in a dry nursery and transplanted into the main field. The transplanting method and field management of the dry nursery seedlings are the same as for the submerged nursery seedlings.

a) Nursery preparation and sowing

Nursery fertilization. Organic fertilizers are the major nutrient source for fertilizing the nursery: 3 to 5 kg chopped rice straw and manure per m^2 is applied during the preceding autumn or winter. Three days before sowing the nursery bed is prepared. The width of the bed is 1.4 m and 24 g N, 24 g K and 27 g P are applied as base fertilizer per m^2.

Soil preparation. Soil is prepared in the preceding winter and needs to be fully dried and trampled into very fine soil particles; 15 kg fine soil is needed per m^2: 7.5 kg fine soil for adjusting soil pH and another 7.5 kg for covering the seeds after sowing. Each m^2 of nursery seedlings is sufficient to plant 25 (late season rice) to 50 (early season rice) m^2 rice field.

Sowing. To prevent diseases it is necessary to adjust soil pH. A special pH regulator is applied together with 7.5 kg of fine soil before sowing. Fenaminosulf is also effective in preventing rice seedling rot, caused by Fusarium spp. Seed is soaked for 1-2 days but germination is not necessary. Another 7.5 kg of fine soil is used to cover the seed after sowing.

Nursery management. The nursery bed is maintained moist before the second leaf emerges. Rice straw is used to cover the nursery bed to keep the soil moist for the late season rice. Irrigation or watering will not start until the leaf is curly. Before transplanting, 2 g N is applied to the nursery bed. Generally, seedling age at transplanting is less than 30 days.

b) Physiological characteristics of dry nursery seedlings for transplanting

Raising seedlings in dry nurseries not only saves water but also may result in higher grain yields (Zhou, 1997) (Table 6.3). As the aeration characteristics of the dry nursery soil are better than those of the submerged nursery soil, seedlings from the dry nursery have more roots, higher root weight and longer roots. There is almost no recovery stage after transplanting of dry nursery seedlings because of their well-developed roots (Table 6.4). Higher yields are attributed to the higher panicle number, as there is no recovery stage for dry nursery seedlings, so that more effective tillers are produced.

6.3.1.2 Dry nursery seedlings for throwing (tray seedlings)

Generally, varieties with a long growth have a higher dry matter production and grain yield than varieties with a short growth. The nursery stage can extend the growth duration and sunlight is used more efficiently, which is very important in the double season rice of Jiangxi province. Throwing seedlings is a new cultivation method developed in recent years. It not only maintains the advantage of transplanting seedlings (i.e. extending the growth period), but it also is saving labor. Farmers have adopted the method of throwing seedlings very fast. The seedlings for throwing are raised under reduced water supply.

Table 6.3. Grain yield and yield component of dry nursery seedlings (Zhou, 1997).

Nursery type	Panicles per m^2	Spikelets per panicle	Filled spikelets (%)	1000-grain weight (g)	Grain yield (kg ha^{-1})
Dry nursery	396	88.3	78.2	21.0	6505
Submerged nursery	354	87.9	72.0	21.0	6210

Table 6.4. Physiological characteristics of dry and submerged nursery seedlings (Zhu, 1998, Zhou, 1997).

Nursery type	Number of leaves	Seedling height (cm)	Number of roots per plant	Plant weight (g)	Recovery time (d)
Dry nursery	4.5	18.5	12.1	22.1	0
Submerged nursery	4.8	19.7	9.4	16.8	4

a) Nursery preparation and sowing

Nutrient application. Nutrients have to be applied and mixed with the soil before sowing.

Sowing tray. The sowing tray is made of plastic. Each tray has 561 holes and allows planting of 15 m^2 rice field.

Nursery bed. Two types of nursery beds exist. One is the dry nursery bed, which is almost the same as the bed for transplanting. The other bed is prepared similar to the traditional submerged bed. Before sowing, surplus water is drained from the submerged nursery to keep the bed moist.

Sowing. (a) Dry sowing. The dry nursery bed is watered at least 10 cm deep. After the surface soil is made sticky, the tray is placed on the bed. Two third of the nutrient-enriched soil is put into the tray holes before sowing. After sowing, the remaining soil is used to cover the seeds while the soil is kept moist. (b) Wet sowing. Wet sowing is simple. The tray is put on the surface of the moist nursery. The sticky soil from the moist nursery is used to fill the tray holes and the seeds are put into the holes. After sowing, the seeds are pressed into the soil.

Nursery management. The nursery bed is kept moist up to second leaf emergence. Rice straw is used to cover the nursery bed to keep the soil moist for the late season rice. Watering will not start until the leaf is curly.

b) Physiological characteristics of tray seedlings

Grain yield of tray seedlings is higher than that of submerged nursery seedlings (Table 6.5). This is attributed to a higher number of panicles, as throwing of seedlings often increases the plant number per m^2 and a higher number of effective tillers produced at an early growth stage. The quality of tray seedlings is also better than that of submerged nursery seedlings (Table 6.6).

Table 6.5. Grain yield and yield components of tray seedlings and seedlings from submerged nurseries (Fu, 1998).

Nursery type	Number of panicles per m^2	Number of spikelet per panicle	Filled spikelets (%)	1000-grain weight (g)	Grain yield (kg ha^{-1})
Tray seedlings	368	96.0	86.0	28.0	8490
Submerged nursery	315	108.8	82.0	27.8	7815

Table 6.6. Physiological characteristics of tray seedlings and seedlings from submerged nurseries (Fu, 1998).

Nursery type	Seedling age (d)	Seedling height (cm)	Stem width (cm)	Fresh weight (g)	Total number of roots per plant	Number of white roots per plant
Tray seedlings	28	16.5	0.28	0.270	11.4	9.9
Submerged nursery	28	17.7	0.26	0.265	9.7	2.4

6.3.2 Interval irrigation

Recently, interval irrigation is one of the water-saving management methods for rice fields recommended by extension services. It may result in increased grain yields and reduces total water requirements (Table 6.7). Details of the management are as follows: (a) Recovery stage. Shallow water is needed, which is maintained up to about 5-7 days after transplanting of dry nursery seedlings. For rice fields planted with thrown seedlings, water is drained about 3 days after throwing. (b) After the recovery stage. At both the dry nursery seedling and throwing seedling fields, an interval irrigation is started. Each time, 2-3 cm of water is applied. Irrigation starts again 2-3 days after water drains naturally. c) Drying of the field. When total plant number per unit area reaches 70-80% of the predetermined panicle number, water is drained.

Table 6.7. Grain yield and water production efficiency of submerged and interval-irrigated rice fields (Wang, 2000).

	Irrigation amount (m^3 ha^{-1})	Grain yield (kg ha^{-1})	Water production efficiency (kg m^{-3})
Submerged irrigation	13500	8049	0.596
Interval irrigation	9600	10401	1.083

Tiller production will slow down when the soil water content is reduced and will stop when the field is dry. This increases the tiller to panicle ratio. Normally, interval irrigation starts again when the leaves become curly or when the second leaf from the top emerges until one week before harvest.

According to Li (2000), raising of dry nursery seedlings and throwing seedlings together with interval irrigation management can reduce water requirements by 32.72% and 32.54%, respectively, and reduce input costs by 490.8 and 922.7 Chinese yuan ha^{-1}, respectively.

Based on water requirement characteristics, rice can be subdivided into two types, irrigated and upland rice. Upland rice is normally grown under dry conditions and irrigated rice is grown under irrigated conditions. Experiments showed that irrigated rice can produce high yields under dry conditions as long as there is irrigation at the critical stages, such as spikelet initiation and heading (Tu, 2000). Varieties with well-developed and deep roots are necessary for such cultivation methods of irrigated rice.

6.4 Further research objectives for water-saving rice cultivation

1. Varieties for water-saving conditions.

(a) Drought-resistant varieties

Some of the currently grown upland varieties have a strong drought-resistance (Chen, 2000). The later generations of Indica and Japonia hybrids have both drought-resistance and cold-tolerance genes,

which is a good starting point for selection of drought-resistant varieties (Wang, 2000). Root characteristics and plant type are also suitable criteria for selection.
(b) Short-growth varieties
Short-growth varieties can reduce the quantity of required irrigation water. Normally, long-growth varieties have higher grain yields than short-growth varieties. In recent years, new short-growth varieties reacted the same or even higher yields than long-growth varieties. If breeders can combine short-growth with drought-resistance characteristics, the water saving ability of new varieties will be further improved.

2. Improvement of the fertilizer application technology
Root length is affected by the amount of N applied (Tu, 2000) and root characteristics are affected by the fertilizer type and application methods. Fertilizer applied before transplanting or throwing and mixed with soil may not only save water but may also increase fertilizer efficiency.

3. Improving the water-retention capacity of the soil
The water-retention capacity of sandy and red soils, which are the main soil types in the southern part of China, is very poor. Increase in soil organic matter can save irrigation water (Chen, 2000). It seems, therefore, important to pay attention to soil improvement and not only to irrigation.

4. Chemical regulators for water saving
Research on chemical regulators, such as ABA is important, as spraying of regulators can reduce the evaporation and transpiration of the canopy (Chen, 1985).

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7. Water-saving physiology and high-efficiency management techniques in rice

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Abstract

This paper summarizes the main results of various studies on soil-water-plant relationships and irrigation management in rice. When soil water potentials are higher than -0.025 MPa, rice can maintain physiological processes, such as photosynthesis, nutrient uptake and utilization, and when soil water potentials are lower than -0.025 MPa, these processes are markedly reduced. Here, a soil water potential of -0.025 MPa is considered a water stress threshold value for rice physiology.

Rice yields are affected by the development stage in which water stress occurs. The stages of sex cell formation, effective tillering and early filling are more sensitive than other stages, and a soil water potential between -0.01 and -0.02 is within the optimal range for rice growth and yield formation. During the stages of ineffective tillering, grain filling, middle and late filling, rice yield is not sensitive to water stress, with a threshold of -0.035 MPa. During the stage of branch and floret differentiation, soil water potentials between -0.02 and -0.025 MPa are enough for normal rice growth and yield formation.

A water stress index is defined as the ratio of actual accumulated water stress and maximum accumulated water stress within a growth period, reflecting the joined effects of soil water stress and its duration. This general and reliable concept is useful for research on soil-water-plant relationships, and can be incorporated into crop simulation models or decision support systems.

Field experiments integrating different management practices produced an optimum water-saving irrigation plan for rice production: shallow water layer at returning green stage, a soil water potential of -0.02 MPa or water layer from returning green to effective tillering, between -0.025 and -0.035 MPa from effective tillering to the secondary branch differentiation, between -0.01 and -0.02 MPa from the secondary branch differentiation to day 20 after heading, and between -0.025 and -0.035 MPa from day 20 after heading till maturity. Under this irrigation plan, combined with a source-limited cultivar, proper plant density and fertilizer rate, water use is reduced up to 30% and rice yields are increased by 4% compared to conventional flooding systems.

7.1 Introduction

Although water in the Jiangsu province of China is abundant, the distribution in space and time is uneven. Water availability in the southern part of Jiangsu is higher than in northern part, while an infrastructure for distribution of water is lacking. Even in normal rainfall years, sufficient irrigation water is not assured in all rice areas of Jiangsu. As a result, regional and seasonal water deficits frequently occur. The lack of water in rice growing areas is most severe in Huaibei, in the highlands and along the coast. At present, use of irrigation water in rice paddy fields in Jiangsu is high, and is estimated at 19,500-30,000 m^3 ha^{-1}, while precipitation is 550-640 mm during the rice growing season from June to September (Dai, 1984). Total water consumption is higher than water demand by rice. To use the available water efficiently, maintain the rice area in water deficit zones, and to increase rice yields in Jiangsu, many physiological and crop management studies have been carried out since 1987.

In most physiological studies (Guo *et al.*, 1989; Sun *et al.*, 1990; Zhao & Zhu, 1990; Li & Peng, 1991; Ke, 1992), absolute water content of the soil or field capacity is used to measure soil water. However, these criteria have shortcomings such as the slow testing speed and low precision, which makes real-time soil water measurement very difficult. Since the soil water status is subject to rapid changes and physiological effects differ with soil texture, the use of soil water content as indicator of the soil water status has a limited adaptability. In other studies, soil appearance is used as decision criterion for irrigation, but this method is inaccurate and not easy to quantify and thus has more limitations.

Adoption of the concept of soil water energy in studies on water physiology and irrigation technology in rice provides a rapid and precise methodology for measuring and monitoring the soil water status, and gives useful results that are less limited by soil type and thus have a general meaning. In China, the use of the water energy concept started in the 1980s to investigate the relationships between soil water potential and emergence and seedling growth in dry-land crops such as wheat (Deng, 1988). This paper reports the main results of research on soil water potential measurements and the performance of rice.

7.2 Methodology

First, relationships between soil water potential and rice yield formation were identified. Subsequently, soil water potential criteria for water-saving irrigation were determined and modified based on data from repeated experiments at multiple sites. On the basis of these experiments, water-saving and high-efficiency irrigation regimes were formulated and applied in different areas of Jiangsu.

Methods used in the studies include i) controlled water potential pot experiments, ii) controlled water potential experiments in micro-plots, iii) water stress experiments in solution culture, and iv) field plot experiments and large-scale demonstration trials. In the experiments, basic research into the physiological mechanisms of yield formation was integrated with applied agronomic research so that results not only contribute to understanding of the eco-physiological mechanisms, but also to development of practical techniques that both reduce water requirements and increase yields.

7.2.1 Controlled water potential experiments in pots

Experiments were conducted from 1989 to 1995. The height and diameter of the pots were 30 and 25 cm, respectively, with 15 kg loamy soil each. In each pot, three hills of 35-days old rice seedlings were transplanted, with two seedlings per hill for normal rice cultivars and one seedling for hybrid rice cultivars. To monitor soil water status, a vacuometer-style negative pressure meter was installed in the pot, with the meter head buried at 10 cm from the soil surface. Daily, at 8, 12 and 18 h, the negative soil water pressures were recorded. When the measured soil water potential was lower than a pre-set value, irrigation was started to maintain soil water potential within four pre-set ranges: -0.015, -0.025, -0.045 and -0.065 MPa, plus a control with a permanent water layer. Duration of the treatments was ten days, and before and after the treatments, a 3 cm water layer was maintained in the pots. According to seven rice development stages, the experiment was divided into: middle tillering, late tillering, branch initiation, reproductive cell formation, meiosis, pollen formation, and late filling. During the experiment, observations and measurements were made to characterize the effects of soil water stress on rice physiology and biochemistry, growth and yield.

7.2.2 Controlled water potential experiments in micro-plots

Experiments were carried out from 1992 to 1997. Plot areas were 3.34 m^2, with a 80 cm layer of loamy soil. To monitor the soil water status, two vacuometer-style negative pressure meters were installed in the plot, with the meter head buried at 10 cm from the soil surface. Observations were made daily

between 8 and 9 and between 17 and 18 h. Supplementary water was provided whenever necessary to maintain designed soil water potentials of -0.015, -0.025 and -0.045 MPa, plus the control with a permanent water layer. In each plot, 98 hills of rice seedlings were transplanted, with the row and within-row spacing of 20 and 17 cm, respectively. Per hill, three seedlings (regular cultivar) and one seedling (hybrid) of 35 days were transplanted. Water status was controlled from returning green stage till maturity. During the experiments, observations and measurements were made to determine effects of soil water stress on rice physiology and biochemistry, growth and yield formation.

7.2.3 Water stress experiments in culture solutions

These experiments were conducted from 1990 to 1993. The culture solution was formulated according the prescription provided by IRRI. Rice was planted in foam board and fixed with sponge, the row and within-row spacing were 24 and 9.5 cm, respectively. Before treatment, the rice plants were placed in the micro-plots without PEG (polyethyleneglycol) 6000, then moved to the treatment micro-plots where PEG6000 concentrations were maintained at five osmotic potential levels: 0, -0.1, -0.15, -0.20 and -0.25 MPa (equal to soil water potentials of 0, -0.026, -0.039, -0.052 and -0.065 MPa). After treatment, plant roots were washed by ion-free water and then moved back to the micro-plots without PEG6000 till maturity. The treatments were imposed at different rice development stages to study the effects of water stress on the nutrient uptake by the plant.

7.2.4 Field experiments

Three types of experiments were conducted in eight different rice areas from 1995 to 2000. The first type of experiments with intermittent irrigation used the same soil water potential levels during all development stages. The fields were irrigated (3 cm) when the soil water potential was lower than the treatment level. The experiment consisted of four soil water potential (treatment) levels, -0.015, -0.025, -0.035 and -0.045 MPa, plus the control with a permanent water layer (3 cm). This experiment was designed to study the relationships between water-stress intensity, rice growth, development and yield formation.

The second type of experiments encompassed intermittent irrigation and different soil water potential levels during four different development stages. The development stages included effective tillering, ineffective tillering to secondary branch differentiation, secondary branch differentiation to day 20 after heading, and day 20 after heading to maturity. The experiments were designed to observe the effects of different irrigation regimes on rice yield and water-use efficiency.

The third type of experiments aimed at improving management efficiency using different irrigation regimes, fertilizer levels, cultivars and plant densities. These experiments were conducted as a split plot design, with the irrigation regime as main plots, plant density or fertilizer as subplots and cultivars as sub-subplots. The treatments consisted of two cultivars, i.e. Xianyou 63 (1 seedling per hill) and Yangen 2 (2 seedlings per hill), two fertilizer levels, i.e. 187.5 and 300 kg N ha^{-1}, two plant densities, i.e. 13.3×25.0 and 13.3×16.7 cm, and two irrigation regimes, i.e. normal and water-saving irrigation. With the normal irrigation, water potentials between -0.025 and -0.035 MPa were maintained during returning green stage and from effective tillering to the secondary branch differentiation, and a water layer was maintained during the other stages. With the water-saving irrigation, a shallow water layer during returning green stage was maintained. From returning green to effective tillering the water potential was maintained at -0.02 MPa, from effective tillering to secondary branch differentiation between -0.025 and -0.035 MPa, from secondary branch differentiation to the day 20 after heading between -0.01 and -0.02 MPa, and from day 20 after heading till maturity between -0.025 and -0.035 MPa.

7.3 Main results

7.3.1 Water stress and active oxygen metabolism

It is generally assumed that water stress increases the active oxygen content in plant tissues, damages and enhances the penetrability of cell membranes and strengthens the activation of enzyme oxide (McLord *et al.*, 1969). In the pot experiments, penetrability of the rice leaf plastid membrane, activation of super oxide dismutase (SOD) and catalase enzyme (CAT), malondialdehyde content (MDA) and oxygenation ability under low soil water level were measured. The results show that at soil water potentials higher than -0.025 MPa, active oxygen metabolism does not differ much from the control of 0 MPa (Fig. 7.1). With water potentials below -0.025 MPa, damage to the rice leaf cell membrane is observed, penetrability of leaf cell membrane increases and continues to increase with increasing water stress. There is a significant linear relationship between electric conductivity of leaf exosmosis liquid (y, %) and soil water potential (x, MPa): $y = 11.9099 - 36.3966\ x$, $r^2 = 0.9867^{**}$(Xianyou 63). With higher penetrability of the leaf cell plastid membrane, the content of SOD and CAT in the leaves increases (Fig. 7.1). A similar pattern is obtained at different development stages and with other cultivars. Water stress has less effect on MDA than on SOD and CAT. Compared to the control, MDA content in the leaves is higher before milk stage with a maximum value at heading stage. After the milk stage, the MDA content changes inconsistently.

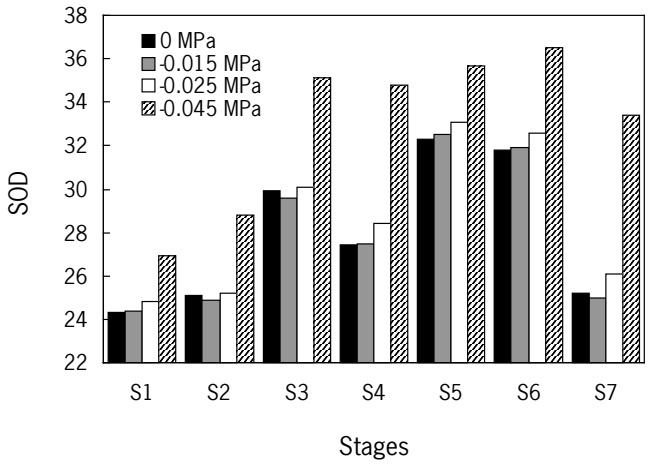

Figure 7.1. Effect of water stress at different development stages on activity of SOD (enzyme unit·g⁻¹fresh weight). Development stages: S1 = tillering, S2 = spike differentiation, S3 = secondary branch differentiation, S4 = heading, S5 = grain filling, S6 = milk, S7 = yellow ripening.

Root oxygenation ability is an indication of root viability and activity in rice. The oxygenation ability of α-NA was measured in roots down to 5 cm deep. Figure 7.2 shows that the effects of low soil water potentials on root oxygenation ability differ with cultivars and development stage. During the meiosis stage, low soil water potentials reduce the root oxygenation ability of Xianyou 63 and Yangen 2. During the stage of heading, the oxygenation ability of both cultivars is similar. During the early filling stage, the oxygenation ability of Yangen 2 decreases, but that of Xianyou 63 increases. During the middle and late filling stages, root oxygenation ability of both cultivars under low water potential is higher than in the control, indicating that low water potentials delay the senescence of rice roots.

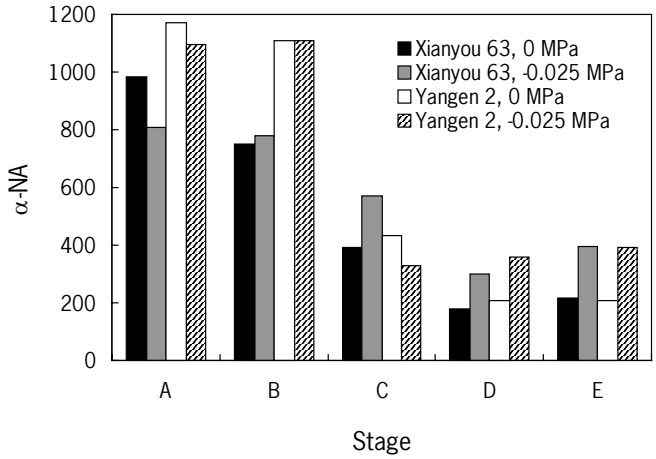

Figure 7.2. Root activity, i.e. α-NA oxidizing power (in $\mu g \cdot g^{-1} \cdot s^{-1}$) during different development stages under two soil water potential levels for two cultivars. Development stages: A = reduction division, B = heading, C = early grain filling, D = middle grain filling, E = late grain filling.

7.3.2 Water stress and free proline content in leaves

The free proline content in the leaves of the cultivars Xianyou 63, Yayou 2, Zhengzhuai and Yangen 2 were measured on day 15, 25, and 35 after treatment in pot experiments (Table 7.1). The results indicate that effects of low soil water potentials on leaf free proline content differ among cultivars and treatments. After enforcing low soil water potentials, leaf free proline content of all cultivars increases with decreasing soil water. Among the four cultivars observed, the relative free proline content is highest in Zhengzhuai and lowest in Yangen 2. Further analysis shows that yield reduction under water deficit conditions is less in cultivars with a higher relative proline content. There is a significant negative correlation between the relative free proline content and yield decrease ($r = -0.9506^{**}$). Zhengzhuai showed high leaf photosynthesis and daily dry matter accumulation. These results indicate that relative proline content in leaves of Zhengzhuai is associated with drought tolerance. Thus, relative free proline content under long periods of water stress can be used as a criterion to identify genotypic drought tolerance in rice. Further research should indicate whether relative proline content under long periods of water stress is a critical criterion.

Table 7.1. Effects of soil water stress on free proline content ($\mu g \, g^{-1}$ dry weight) in leaves of different rice cultivars. Average of 3 measurements on day 15, 25, 35 after enforcing water stress.

Soil water potential (MPa)	Xianyou 63		Yayou 2		Zhengzhuai		Yangen 2	
	Absolute content	Relative content (%)	Absolute content	Relative content (%)	Absolute content	Relative content (%)	Absolute content	Relative content (%)
0	615.6	100.0	474.6	100.0	498.6	100.0	612.4	100.0
-0.015	748.0	121.5	554.8	116.9	640.7	128.5	694.5	113.4
-0.025	845.2	137.3	624.1	131.5	786.3	157.7	750.8	122.6
-0.045	890.1	144.6	708.9	149.5	831.2	166.7	924.1	150.8
-0.065	961.3	156.2	709.7	149.5	926.0	185.7	949.9	155.1

7.3.3 Low water potential and photosynthesis

7.3.3.1 Photosynthetic rate

In pot experiments with the cultivar Yangen 2, net photosynthetic rate during the grain filling stage was measured for different soil water potentials and light intensity levels (Fig. 7.3). The slope of the light response line was highest and lowest when soil water potential was 0 and -0.045 MPa, respectively, and the effect of light on photosynthesis decreased rapidly with increasing water stress.

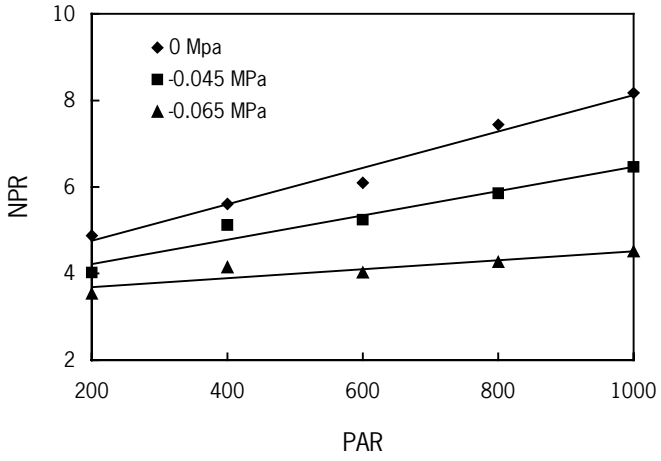

Figure 7.3. Photosynthesis in relation to light intensity under different soil water potentials. PAR= Photosynthetic Active Radiation; NPR= Net Photosynthetic Rate (μmol·m^{-2}·s^{-1}).

The net photosynthesis and stomatal conductance for the 2nd leaf from the top in the cultivar Shanyou 63 was measured with a LI-COR 6200 portable photosynthesis system under different soil water potentials, i.e. 0 and -0.045 MPa. Two equations were derived for the relationship among photosynthetic rate and light intensity and stomatal conductance.

For a soil water potential of 0 MPa:

$$Y = -8.7 + 33.83X_1 + 2.94 * 10^{-3}X_2 - 1.76 * 10^{-3} X_1X_2 - 1.03 * 10^{-6}X_2^2 \qquad R^2 = 0.9999$$

For a soil water potential of -0.045 MPa:

$$Y = -11.18 + 64.01X_1 + 0.0194X_2 - 0.048X_1X_2 \qquad R^2 = 0.9797$$

where Y = net photosynthesis (μmol CO_2 m^{-2} s^{-1}), X_1 = stomatal conductance (molH_2O m^{-2} s^{-1}), X_2 = photosynthetic active radiation (μmol Photons·m^{-2}·s^{-1}).

Based on the above equations, the increase in net photosynthesis was determined under different light and water conditions by one unit increase in stomatal conductance (P/C). The results indicate that effects of light intensity on leaf P/C were low when rice is supplied with sufficient water. However, under water-deficit conditions and increasing light intensity, leaf P/C decreases markedly and the effect on net photosynthesis was gradually weakened. When the photosynthetic active radiation was 1200 μmol photons m^{-2} s^{-1} no distinct effect on net photosynthesis was observed.

7.3.3.2 Leaf chlorophyll content

The chlorophyll content was measured in leaves of Xianyou 63 cultivated in pots. The results indicate that the leaf chlorophyll content before heading is almost similar under different water treatments. For example, the average leaf chlorophyll contents under soil water potentials of 0, -0.025 and -0.045 MPa were 2.81, 2.8 and 2.75 mg dm^{-2}, respectively. After heading, the difference in leaf chlorophyll content between the different treatments increases gradually, with the largest difference at milk stage. Leaf chlorophyll contents in treatments with soil water potentials of -0.025 and -0.045 MPa decrease by 5.2 and 14.1% respectively, and they remain unchanged under a soil water potential of -0.015 MPa compared to the control (0 MPa). This pattern indicates that water stress accelerates leaf senescence after heading.

Although the impact of water stress on leaf chlorophyll content before heading is low, the ratio of chlorophyll a/b was significantly different between water stress treatments and control. In treatments with soil water potentials of -0.025 and -0.045 MPa, leaf chlorophyll a/b increases before and during heading by 3.8 and 7.0% and during milk stage by 11.7 and 20.4%, respectively, compared to the control. In treatments with soil water potentials of -0.015 MPa, even at milk stage, the chlorophyll a/b ratio was only slightly lower than in the control. The same trend was observed in the leaf chlorophyll contents of other cultivars.

7.3.4 Water stress and the uptake of nutrients

$^{15}NH_4NO_3$ was supplied in a solution culture during the stages of tillering and booting and $NaH_2{}^{32}PO_4$ $2H_2O$ was supplied during the heading and milk stage to determine the impact of water stress on the uptake of nutrients including nitrogen, phosphorus, potassium, iron, manganese, copper and zinc. The results (Fig. 7.4) show that with anosmotic potentials of -0.1 MPa during tillering stage, nitrogen use efficiencies of $^{15}NH_4NO_3$ of leaves, stems, sheaths and roots are equal to or slightly lower than the control. Therefore, -0.1 MPa can be regarded as a water potential threshold for rice nitrogen uptake during the tillering stage. With increasing water stress, uptake of nitrogen in rice is further reduced. During the stages of booting and grain filling, nitrogen use efficiency also decreases rapidly when the water potential drops below -0.1 MPa. The impact of water stress on nitrogen uptake decreases from spike, stem, to sheath and leaf.

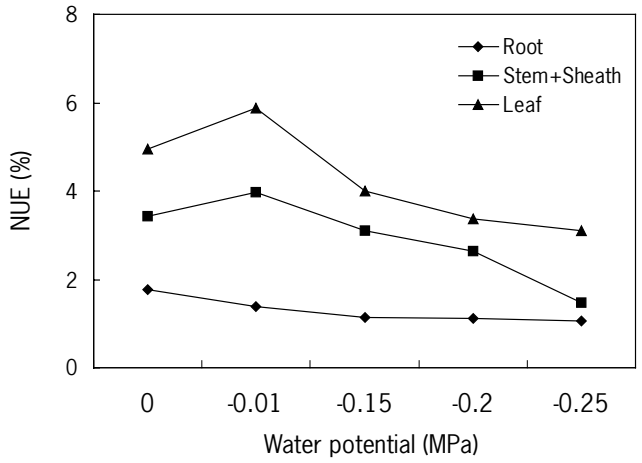

Figure 7.4. Effect of water stress on Nutrient Use Efficiency (NUE) of rice at tillering stage.

The radioactivity of ^{32}P in plant organs during the milk and near-maturity stage were also measured. Fig. 7.5A shows that in the low water potential treatment, ^{32}P in root, stem, leaf and sheath during milk stage is lower than the control (water potential of 0 MPa) and, hence, the P uptake rate decreases with increasing water stress. The same result was obtained during the stage of late grain filling.

The potassium content in crop parts during the stages of booting and grain filling were also measured. During the stage of booting, the potassium content of all crop parts except roots decreased with increasing water stress (Fig. 7.5B), in decreasing order: sheaths > stems > leaves > panicles > roots. This indicates that potassium uptake in sheaths and stems during the stage of booting is more sensitive to water stress than uptake by other organs. During the stage of grain filling, potassium concentrations in all organs except root and panicle decreased with increasing water stress, which is consistent with the data obtained at the booting stage.

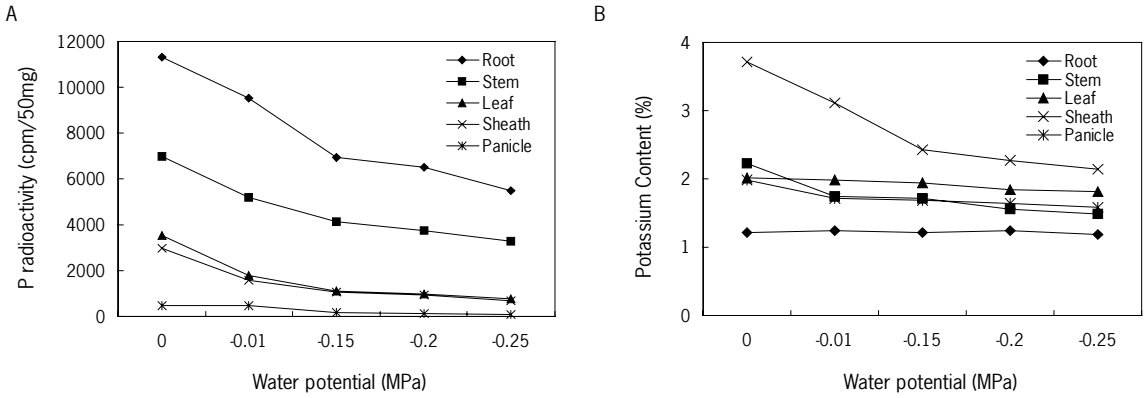

Figure 7.5. Effect of water stress on uptake of 32P by rice at milk stage (A) and effect of water stress on potassium content of rice organs at booting stage (B).

The effects of water stress on the uptake of iron, manganese, copper in panicles after heading and on the uptake of zinc during tillering stage were also studied in the experiments, but no significant effects on their uptake were observed.

7.3.5 Water stress index under intermittent irrigation

Generally, soil water content and soil water potential are used to indicate the level of water deficit in a soil. These indices can express the soil water status at a given moment, but do not indicate the impact of the duration of soil water stress on rice growth and yield. The effect of soil water deficit on rice should be considered from two points of view: soil water status and its duration. This resulted in formulation of a water stress index (WSI, see Wang, 1992; 1994):

$$WSI = \frac{W_M \sum_{j=1}^{n} T_j - 0.5 \sum_{j=1}^{n} \sum_{i=1}^{T_j} (W_{j(i)} + W_{j(i-1)})}{T_M \cdot (W_M - W_D)}$$

where W_M = field saturation (or soil water potential of 0 MPa); W_D = wilting point (or wilting soil water potential), T_M = days of a development stage, n = number of days of water deficit within T_M; T_j = duration of the j^{th} water deficit, $W_{j(i)}$ = actual soil water content or water potential on the i^{th} day within duration of the j^{th} water deficit.

Using the experimental data described, water stress criteria during the stages of effective tillering and meiosis were calculated. The results show a significant correlation between WSI and yield ($|r|>0.9$), which is better than the correlation between soil water potential (or soil water content) and yield (Table 7.2).

Table 7.2. Correlation coefficients between water stress index (WSI), soil moisture, soil water potential and rice yield at two development stages of different cultivars.

Indicator	Effective tillering			Meiosis		
	A	B	C	A	B	C
WSI	-0.9165**	-0.9308**	-0.9587**	-0.9402**	-0.9143**	-0.9218**
Soil water potential	0.7721**	0.8035**	0.7204*	0.7943**	0.6391*	0.7147*
Soil moisture content	0.6350*	0.6101	0.5273	0.6214	0.6427*	0.5598

Where A = Xianyou 63 in Baijiang soil (1989), B = Yangen 2 in loamy soil of controlled plots (1997), C = Zhengzhuai in sandy soil of pot (1995)

7.3.6 Interaction effects between water-saving irrigation and cultivar, plant density and nitrogen

The yield effects observed in field experiments can be summarized as:

1. Interaction between irrigation regime and cultivar. With a sink-limited cultivar such as Yangen 2, yields under normal irrigation are higher than under water-saving irrigation, whereas with a source-limited cultivar such as Xianyou 63, the opposite effect is observed. This indicates that water stress has a greater impact on sink-limited cultivars and thus, water-saving irrigation may be more suitable for source-limited cultivars (e.g. Xianyou 63 and Yayou 2).
2. Interactions between the irrigation regime and plant density. Under water-saving irrigation, yields of sink-limited cultivars realized with high plant densities are higher than the yields with low plant densities. With source-limited cultivars such effects are not observed. Thus, water-saving irrigation combined with sink-limited cultivars require proper plant densities.
3. Interaction effects between irrigation regime and nitrogen. Under water-saving irrigation, 187.5 kg N ha^{-1} result in 11% yield decrease compared to normal irrigation. In contrast, with 300 kg N ha^{-1} yields increase 1% under water-saving conditions compared to normal irrigation, which is 4-5% higher than with 187.5 kg N ha^{-1} and normal irrigation. This suggests that fertilizer applications can compensate the effects of water stress.

7.3.7 The relationship between soil water stress and different development stages

The effects of soil water stress during different development stages on yield were measured in three cultivars: Xianyou 63, Yayou 2 and Yangen 2. The results show that before heading, the sensitivity to low soil water increases from reproductive cell formation, effective tillering, floret differentiation, branch differentiation, pollen filling, to ineffective tillering. During tillering and reproductive cell formation, yields decrease when the duration of a soil water potential below -0.025 MPa is ten days or more. After heading, early filling stage is more sensitive to water stress than the middle filling stage, and the late filling stage is insensitive to water stress. Moderately low soil water stress tends to accelerate grain filling (Fig. 7.6). Source-limited cultivars, i.e. Xianyou 63 and Yayou 2, are more sensitive to water stress during the late stage of filling than sink-limited cultivars, i.e. Yangen 2.

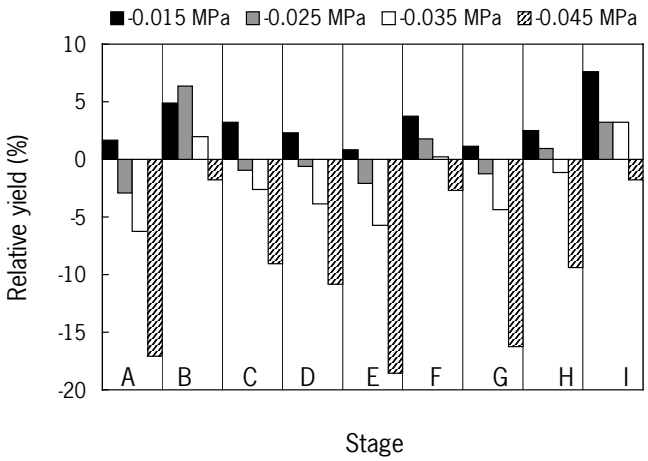

Figure 7.6. *Relative yield under different soil water treatments and during different development stages. Relative yield = (value in treatment - value of control treatment)/value of control treatment * 100. Control treatment is without water stres.; Development stages: A = effective tillering, B = ineffective tillering, C = branch initiation, D = spikelet initiation, E = sex cell forming, F = pollen filling, G = early grain filling, H = middle grain filling, I = late grain filling.*

Based on the yield effects as a result of enforcing different soil water potentials, several irrigation plans were designed. Subsequently, multi-factorial experiments combining different irrigation plans, cultivars, densities and fertilizer rates were carried out in eighteen sites of Jiangsu to determine proper combinations. Based on these experiments, the optimum irrigation plan was selected and its soil water potential during all stages was quantified (Fig. 7.7).

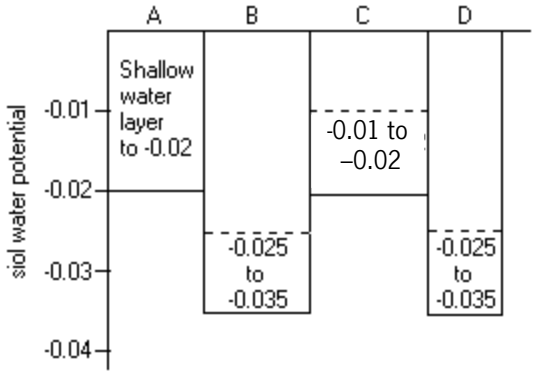

Figure 7.7. *Required soil water potential ranges during different development stages for an optimal water-saving irrigation scheme. Development stages: A = till effective tillering, B = from ineffective tillering to secondary branch initiation, C = from secondary branch differentiation to the twentieth day after heading, D = from the twentieth day to fourth-fifth day after heading.*

Subsequently, the preferred water-saving irrigation plan (Fig. 7.7) was applied in seven counties, which resulted in both water saving (31.1%) and yield increase (4.3%) compared to conventional flooding systems. Results of 1998 experiments are shown in Table 7.3.

Table 7.3. Effects of water-saving technology on yield and water use in seven counties in China.

County	Cultivar	Area (ha)	Yield (kg ha $^{-1}$)	Yield increase (%)	Reduction in water use (%)
Peixian	Shanyou 63	23230	9289.5	3.4	36.3
Ganyu	Shanyou 63	22720	9423.0	4.1	36.9
Binhai	Xuyou 3-2	24090	8830.5	3.2	31.9
Gaoyou	Yanjing 4	45920	7719.0	6.0	30.1
Donghai	Shanyou 63	47300	7953.0	7.4	37.5
Jiangdu	Wuyujing 3	42360	8163.9	2.6	28.0
Taizhou	Wuyujing 3	3310	6991.5	3.6	17.3

7.4 Conclusion and discussion

7.4.1 Water stress threshold for physiological processes

Although the relationship between water stress and plant physiology is complex, a general trend can be derived from our studies. When the soil water potential is higher than -0.025 MPa, the rice plant can perform general physiological processes, such as photosynthesis, nutrient uptake and utilization, equal or better as in the control. When the soil water potential is lower than -0.025 MPa, these processes are markedly reduced. Thus, a soil water potential of -0.025 MPa can be regarded as the water stress threshold for physiological processes in rice.

7.4.2 Water stress threshold for rice yield

The effect of water stress on yield depends on the development stage in which water stress is enforced. The stages of sex cell formation, effective tillering and early filling are more sensitive than other stages. A soil water potential between -0.01 and -0.02 MPa is assumed to maintain normal growth and yield of rice (Fig. 7.6 and Fig. 7.7). During the stages of ineffective tillering, middle and late grain filling, rice yields are not sensitive to water stress. Even when the soil water potential decreases to -0.035 MPa, yields do not decrease. Hence, the water stress threshold for these stages is -0.035 MPa. During the stage of branch and floret differentiation, yield response to water stress is not consistent. When the soil water potential drops below -0.025 MPa yields tend to decrease. Therefore, a water stress threshold between -0.02 and -0.025 MPa is assumed. Differences among cultivars are small so that the same threshold can be applied for different cultivars.

7.4.3 Importance of water stress index under intermittent irrigation

A water stress index is defined as the ratio of actual accumulated water stress to the theoretically maximum accumulated water stress within the entire growing period. This index reflects the joined effect of soil water stress and its duration in the course of intermittent irrigation. Other index methods are based on the soil water level only and ignore the duration of water stress. Therefore, the present concept of water stress index is more general and reliable for research of soil-plant-water relationships and it is of practical use when it is incorporated into crop simulation models or decision support systems.

7.4.4 Soil water potential index under water-saving irrigation

The optimum water-saving irrigation plan for actual rice system is as follows:

- shallow water layer at returning green stage,
- a soil water potential of -0.02 MPa or water layer from returning green to effective tillering,
- between -0.025 and -0.035 MPa from effective tillering to secondary branch differentiation,
- between -0.01 and -0.02 MPa from secondary branch differentiation to day 20 after heading, and
- between -0.025 and -0.035 MPa from day 20 after heading till maturity.

Under this water-saving irrigation plan, combined with source-limited cultivars, proper plant density and fertilizer rate, rice yields increased about 4% and water use was reduced about 31% compared to the control treatment.

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8. Regional allocation of water resources

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Abstract

Agriculture is the largest water user (volume) in many river basins and is further characterized by a strongly variable demand over the year (peak demand), complicating the matching of supply and demand in a region. Changes in agricultural water use can thus have a major impact on the regional water balance.

The usefulness of savings in water due to changed farming methods depends on the spatial configuration of water users, the timing of their water use, the possibilities of storage in a basin -allowing an improved matching of supply and demand involving agricultural and other water users-, and an adequate pre-season planning and real-time management.

In the present paper, effects of changed farming methods on the regional water balance are described for three river basins, viz the Jratunseluna, Serayu and Cidurian basin (Indonesia). In addition, two water allocation models are reviewed that have been applied to these basins:

- **RIBASIM** (RIver BAsin SImulation Model) simulates the water balance of a region or river basin. It is oriented at planning, since it links the hydrological input with the basin water system and allows to analyze the performance of such system as function of the existing or proposed system characteristics.
- **OMIS** (Operational Management for Irrigation Systems) is a crop planning and real-time operational management tool for irrigation schemes.

Realizing the full regional benefit from improvements at farm level requires adequate water allocation management. Both models can contribute to handling the flow of information required to support such water allocation management. Development of a tool, which combines features from both models, would offer even more possibilities for managing regional water allocation problems.

8.1 Introduction

Agriculture is the largest water user in most river basins, particularly in basins where irrigated rice forms the main activity. In many basins competition for water increases and the intensive water use in traditional wet rice cultivation comes into question. Changes in the cropping pattern and changes in technology and or management affecting water use may have a drastic effect on the overall water balance of river basins. Suitable planning and management instruments are required to realize the full benefits for the basin from the improvements made at the micro (farm) level.

This paper focuses on water allocation at a regional scale and the link with the micro (farm) level. Management of the total system is required that should be supported by a decision support tool which structures the process and handles the large data processing requirements. The potential use of two models, RIBASIM and OMIS, both addressing such management decisions is discussed using several case studies.

Section 8.2 describes the application of RIBASIM to the Jratunseluna and Serayu basins. Section 8.3 describes the application of OMIS to the Cidurian basin. Section 8.4 discusses the integration of planning and operation at different levels using features of both models. Section 8.5 summarizes the conclusions of this paper.

8.2 Planning of water availability and water use at regional level

8.2.1 RIBASIM simulation model

Use of RIBASIM in planning

Major components and inter-relationships in planning for a river basin, focusing on multi-sector water supply, are presented in Fig. 8.1.

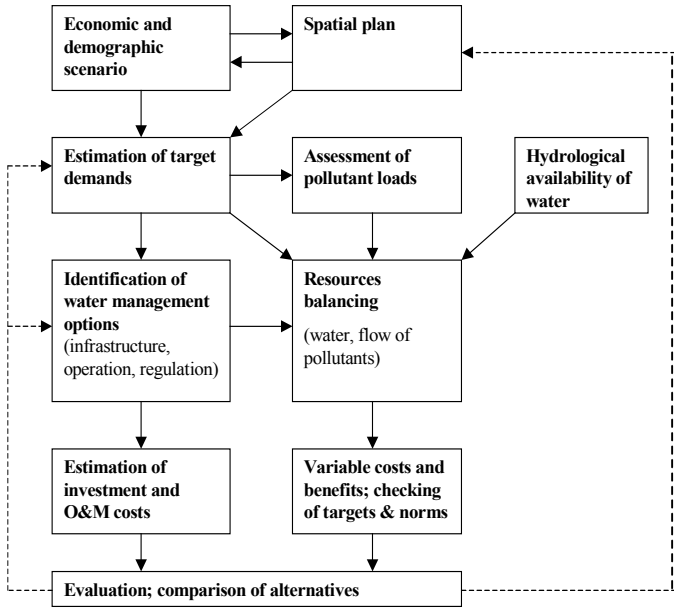

Figure 8.1. Concept for river basin planning – role of RIBASIN.

Planning involves analysis of the available water and estimation of target demands for various users. Estimation of target demands depends on socio-economic projections and developments in different sectors. A spatial plan should indicate the functions and spatial distribution of the activities which together with the associated target demands determine the pollutant load. The proposed set of activities use available resources and determine the impact on a basin. The intended target demands have to be checked or balanced against available resources. Based on an evaluation of this balance and the associated socio-economic performance, an adjustment may be required to optimize the performance by selecting different water management options, adjusting target demands, and/or changing the spatial plan.

The water balance has a strong stochastic component such that the balance and socio-economic consequences need to be evaluated on the basis of a time series representing a series of possible (wet and dry) situations. RIBASIM provides the link between the (stochastic) hydrologic input, the basin water system and its performance.

User interface

The main RIBASIM user interface is presented in a flow diagram (Fig. 8.2) representing the tasks that are required from data entry, simulation to evaluation of the results.

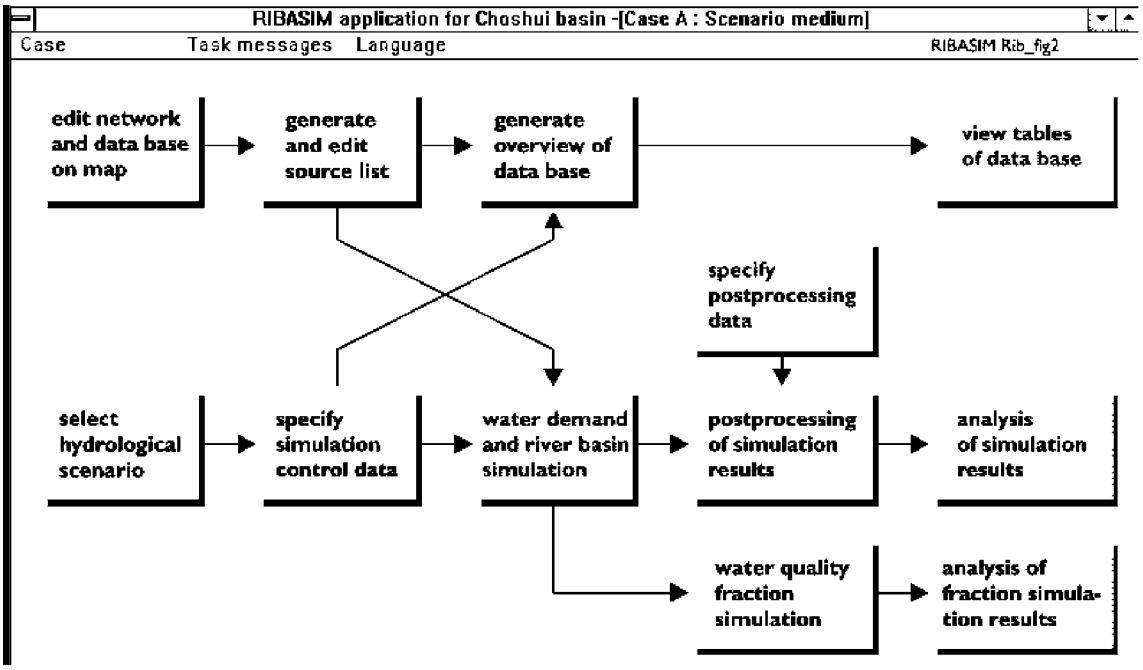

Figure 8.2. Main user interface for RIBASIM.

Schematization

A schematization of water-supplying and -demanding activities in the basin (sources, demands, transport, storage, diversion, hydro-power generation, low flows, etc.) forms the basis for analysis of the water balance and its performance. Fig. 8.3 presents such schematization for the Jratunseluna basin. The branches and a set of different kinds of nodes represent the features of the basin with relevance to the water balance. This network can be adjusted to the level of required detail. The data for each of the network elements can be entered interactively, using the map of the river basin and its network schematization. Water allocation to users can be done in several ways, e.g. a first come first serve basis can be followed along the natural flow direction. This can be amended by, for example, priority allocation to certain users, or priority allocation for a certain portion of the demand, etc.

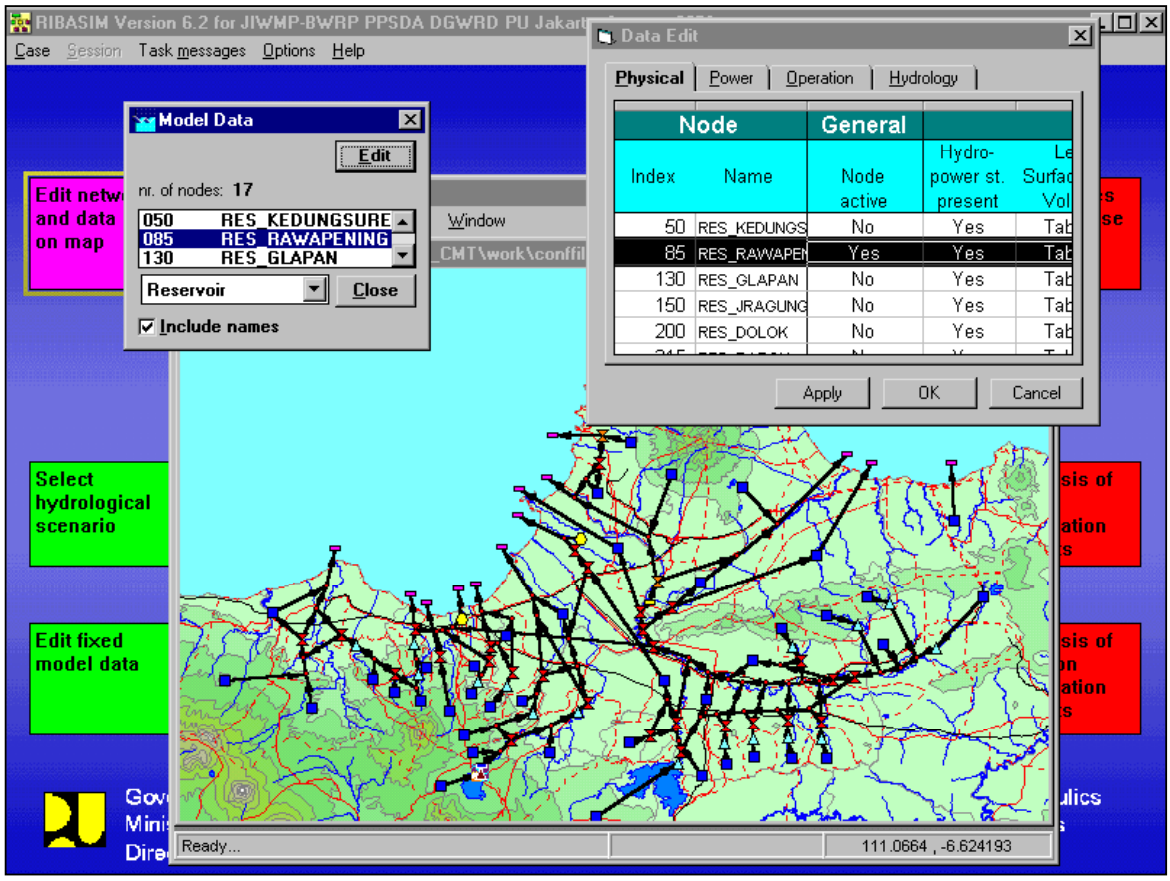

Figure 8.3. Interactive design of a basin network schematization for the Jratunseluna basin (Indonesia).

8.2.2 Application to the Jratunseluna basin

Brief description Jratunseluna basin

Irrigation represents a major activity in the basin, using most of its water resources. Most of the irrigation consists of large schemes (85% > 500 ha). In general, efficiency of water use is low (40 to 50%). Table 8.1 presents the total present and projected cultivated land in the basin. The cultivated area will be influenced by a strong urbanization rate in some parts of the basin.

Table 8.1. Cultivated area Jratunseluna basin.

Type of cultivation	Cultivated area (ha)	
	Base case (1996)	Projected (2025)
Technical irrigated	191,078	178,566
Semi-technical irrigated	61,037	53,915
Rainfed	130,446	130,446
Total	382,561	361,830

Generally, the cropping pattern in the study area is Paddy-Paddy-Palawija ('average' dry land crop). In areas with less water availability the adopted pattern will be Paddy-Palawija-fallow or cultivated with sugarcane. Time shifting is intensively applied to avoid peaks in water demand. The average cropping intensity in the study area is 193% for technical irrigation and 121% for semi-technical; the overall average is 176%.

Options for further agricultural development

Sofar, all potential land is irrigated and has been brought under production. Water availability is the limiting factor to further improve agricultural production. Three main options (as well as combinations) can be followed to increase water supply, viz.:

- increasing water use efficiency in the irrigation process (demand management measure),
- development of new sources of water supply for irrigation (supply oriented measure), and
- adapting the (future) cropping pattern to include less water consuming crops (demand management measure). Such option forms part of the overall change in future agricultural production.

These three options were considered as alternative strategies in the present analysis.

Most effective development

Development of water resources in the basin should address increased requirements for the urban and industrial sector and further support to agricultural development. The most effective strategy to increase water availability to agriculture should be identified, viz. increase efficiency of irrigation water management, implement extra reservoirs, or both.

Because irrigated land is limited, improvements have to be realized through increased irrigation intensity. Repeated simulations with the basin water balance model (RIBASIM) were carried out to determine maximum irrigation intensity for both potential strategies. For both a diversification scenario into non-rice crops was also considered. For adaptation of the cropping pattern a maximum irrigation intensity of 250% has been considered as a realistic maximum in view of the present agricultural practice. Irrigation is by far the largest water user in the basin and that will remain so in the future.

Two sub-strategies have been formulated to test the effectiveness in generating (agricultural) growth: an increase in the efficiency of irrigation water management and implementation of extra reservoirs. They have been considered to improve irrigation water supply in the basin and so to increase the amount of crop area, which can be irrigated. For both sub-strategies a diversification scenario to non-paddy crops is adopted.

Based on repeated trials with the basin water balance model, a revised cropping pattern was designed (for each sub-strategy) which makes maximum use of available water. The results are summarized in Table 8.2. It can be observed that about the same increase in irrigated crop area can be achieved. The cost of implementation, i.e. the effectivity is, however, much different (see later).

Realization of the maximum development potential of the basin, i.e. improved irrigation water management and extra reservoirs, has also been analyzed. In this case, little extra irrigated crop area can be realized, as also can be derived from Table 8.2, due to the combination of limited available irrigated land and its maximum irrigation intensity. At that point only an increase in maximum irrigation intensity can absorb a possible further increase in water supply.

Table 8.2. Increased irrigation potential for the two sub-strategies: improved efficiency and extra reservoirs.

Type of irrigation	Crop type	Base case irrigated crop (ha)	Sub-strategies for agricultural growth			
			Increased efficiency		Extra reservoirs	
			Irrigated crop (ha)	Balance	Irrigated crop (ha)	Balance
Paddy	Paddy	346,802	365,430	18,628	345,479	-1,323
Non-paddy	Palawija	97,131	190,068	92,937	207,682	110,551
	Horticulture		21,119	21,119	23,076	23,076
	Total	443,933	576,617	132,684	576,236	132,304
	Irrigated area (ha)	252,115	232,481		232,481	
	Irr. intensity (%)	176	248		248	

The results from the simulation analysis for the different strategies were used in an economic analysis. Table 8.3 presents a comparison of the effectiveness of investment; investment in improved irrigation water management is clearly much more effective.

Table 8.3. Comparison of the effectiveness of the two strategy options for growth in irrigation.

Strategy option	Net present value generated for each BRp of investment (BRp)
Improved irrigation water management	1.26
Extra reservoirs	0.14

Water balance

The RIBASIM model computes a closed water balance for river basins; Table 8.4 presents the (aggregated) balance for the existing and future projected situation. Water use intensifies from 31 to 40% of runoff (or 17 and 21%, respectively, of total rainfall input). Water use, as fraction of available runoff, is relatively low due to the large seasonal variability of the flow. During the rainy season a large part of runoff flows uncontrolled into the sea.

8.2.3 Application to the Serayu basin

The schematization of the water balance for the Serayu is presented in Fig. 8.4. The water supply situation is quite different from the Jratunseluna basin: there is ample water supply (except for some local situations) and irrigation is already highly developed; practically all land that could be irrigated has been brought under command; existing irrigation intensity is high and well above 200%.

Simulations for the Serayu basin indicate that there is enough water available to increase irrigation intensity substantially, if desired. Expected future changes in the cropping pattern (diversification) will further improve water availability.
For the Serayu basin, available land is the limiting factor, whereas for the Jratunseluna basin water availability is the limiting factor. Such conclusions have important consequences for the way the river basin should be developed.

Table 8.4. Water balance for the Jratunseluna basin.

	Existing situation (1996)		Future situation (2025)	
Hydrological balance ($m^3 s^{-1}$)				
Rainfall input		871		871
Losses	407		407	
Runoff av. to basin / inflow	464		464	
Total	871	871	871	871
Water use ($m^3 s^{-1}$):				
Basin runoff / inflow		464		464
Net consumption				
Agriculture	142		175	
Domestic, municipal and industrial water supply	4		12	
Drainage to sea	318		277	
Total	464	464	464	464

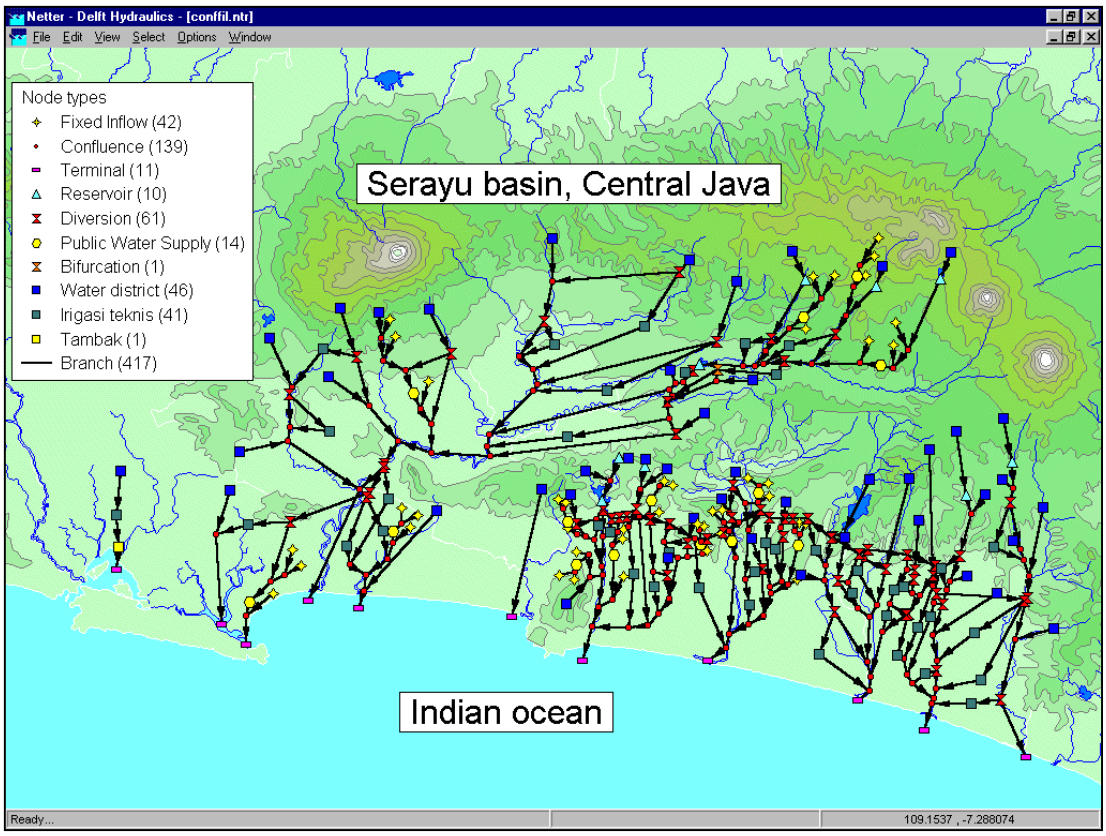

Figure 8.4. Schematization of the water balance for the Serayu basin.

8.3 Crop planning and operational management at scheme level

8.3.1 Brief description Cidurian basin

A location map for the Cidurian basin is presented in Fig. 8.5. The total irrigated area in the basin amounts to 13,000 ha with about 3,000 ha located in small schemes in the upper catchment. Existing irrigation intensity for the Cidurian irrigation scheme (10,000 ha) was estimated at 120%; a much higher intensity may be realised (target 200%) after rehabilitation and improvement of water management.

The flow regime of the Cidurian River is characterised by a fast response to rainfall and a relatively low base flow. Variability in rainfall and runoff are large. During the rainy season dry spells may occur which require careful management to minimise their impact; further, there may be a prolonged period of low flow at the start of the irrigation season (October) which delays field preparation and may jeopardise, eventually, the second crop. Large variations occur at the onset and during the rainy season. There is also a large hourly/daily variation in response to rainfall storms in the catchment.

Due to this uncertainty in water availability and the lack of sufficient information, farmers start land preparation rather late in December/January, after rainfall has saturated the soil and farmers can be assured of a sufficiently continued water supply. As a consequence, water shortages may occur during the second crop and farmers, therefore, plant a second crop for only 50% of the area, of which on average 40% can be harvested (20% of the total area).

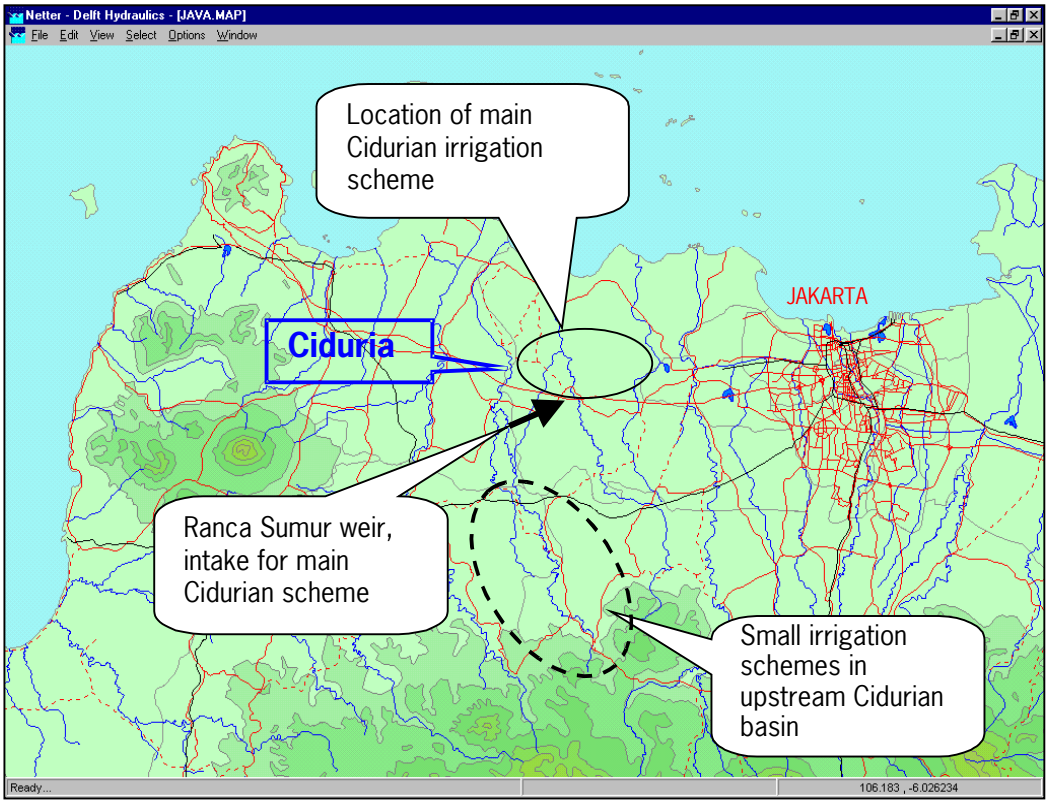

Figure 8.5. Location map Cidurian river basin.

An overall cropping pattern is prepared by the district irrigation service at the start of the irrigation season; it is, however, hard to adjust this plan according to actual field conditions due to a lack of field information in combination with a lack of data processing facilities.

The combined effect of a high variability in water supply and a lack of appropriate information contribute strongly to a loss of control. This has resulted in low cropping intensities and yields, especially in the dry season.

8.3.2 Modeling of operational management

To structure the decision process and improve the required flow of information, the software package OMIS was set up providing full integration of crop planning, monitoring and real-time water allocation. Major management activities for a regular irrigation season are shown in Fig. 8.6. Those include a pre-season planning, subsequent adjustments during the irrigation season based on the monitored status of the scheme, in-season adjustment(s) to the (pre-season) planning, and post-season reporting on performance.

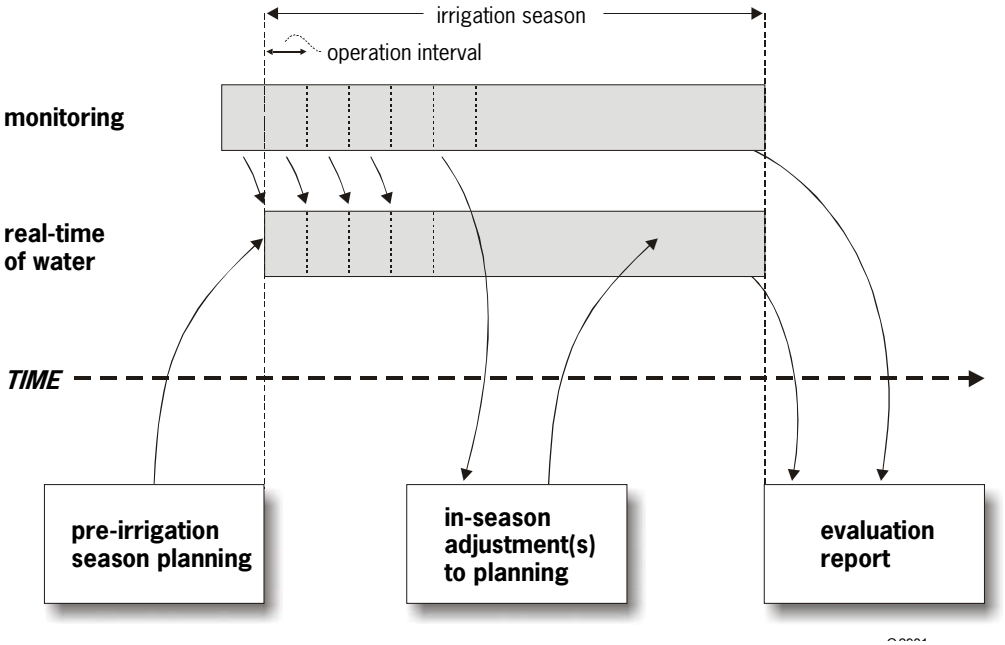

Figure 8.6. Irrigation management activities.

OMIS has been prepared to facilitate the flow of information. OMIS complements a set of forms (Fig. 8.7) which are used to monitor the situation in the field, distribute operation instructions and prepare reports.

Similar to the RIBASIM modeling, a schematization into a network of nodes and branches is used. Fig. 8.8 illustrates the schematization for the Cidurian main irrigation scheme.

Based on the schematization of the canal and drainage system and the individual command areas, the user decides how detailed the distribution of water should be modelled. A schematization into main system and command areas can be followed which typically corresponds with management responsibility between a central (government) agency and farmer groups. Such schematization has obvious advantages when preparing water delivery schedules and operational instructions.

OMIS allows a further sub-division of a command area into fields. A separate water balance is maintained for each of these fields. The fields are considered to receive water in sequence and on the condition that the upper field receives its total requirement. The sub-division allows representation of bottom fields, which may receive less water during drought periods and are thus most susceptible to drought damage.

In OMIS a medium level of detail is used in modeling of the physical flow of water in the irrigation scheme; this matches quite well with the requirements for water accounting and management of the total scheme. Under particular circumstances such as a substantial interaction of the root zone with a high water table, a more detailed computation component may be required.

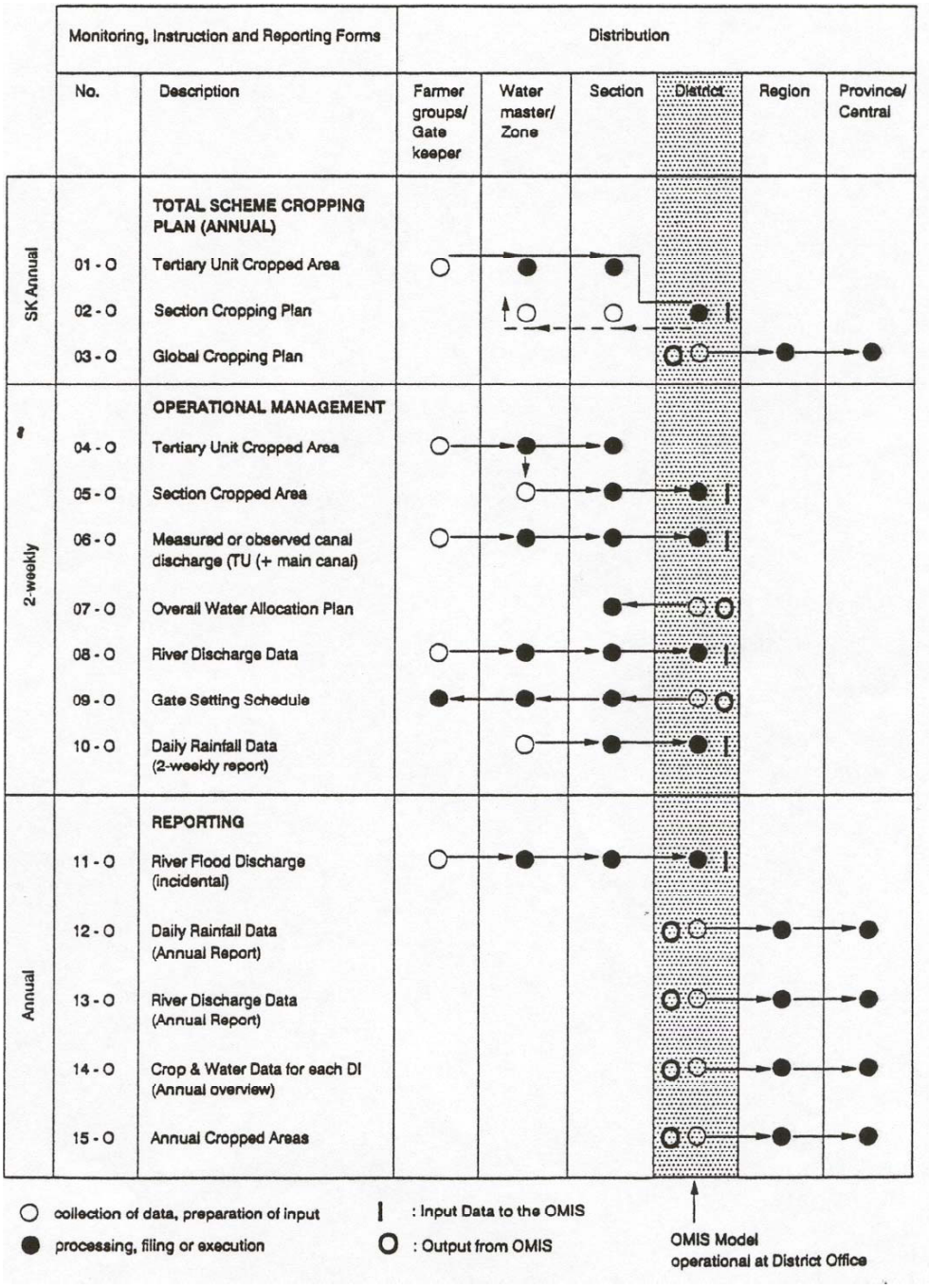

Figure 8.7. Overview of the monitoring, instruction and reporting forms complemented by OMIS.

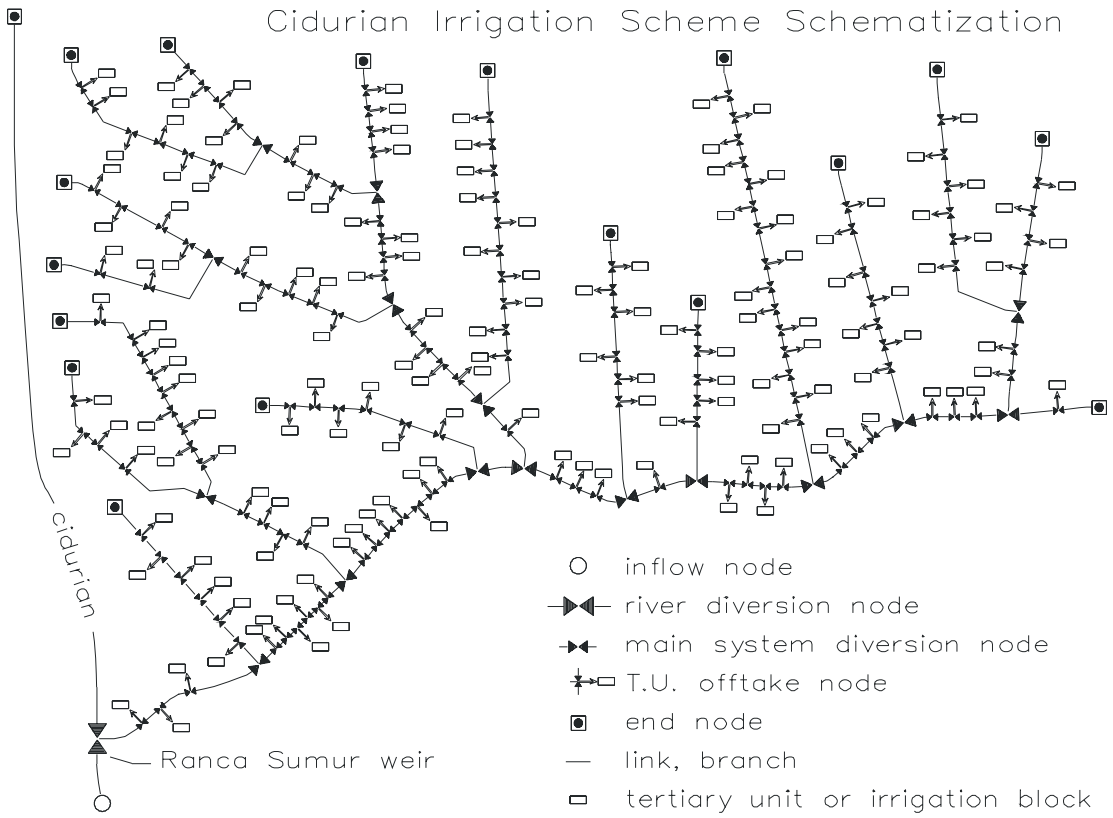

Figure 8.8. Schematization (OMIS) of the Cidurian irrigation project.

OMIS allows on-line preparation of the crop plan based on a graphical presentation of the crop-time diagram on screen and comparison of water requirements with dependable river flow (Fig. 8.9). The monitored crop pattern can be compared with the planned pattern, allowing an efficient in-season adjustment to the planning (e.g. of the second crop). The same monitoring data at successive intervals is used to prepare the adjusted operation schedule for the next interval. The crop-planning module further allows to prepare the plan at Tertiary Unit (TU) level based on the preferences of the farmers. These plans can be aggregated to total scheme level for checking with water availability and policy guidelines for crop planning.

8.3.3 Coordination of water allocation at basin level

An efficient operation of the irrigation scheme and management at basin level becomes increasingly important for an optimal functioning of the individual schemes and an optimum use of the available water. In the Cidurian basin, water is mostly used by the downstream irrigation scheme (10,000 ha) and upstream small irrigation schemes (3,000 ha). The upstream users strongly affect the base flow of the Cidurian during the dry season and dry spells in the rainy season. The cropping pattern for the downstream scheme is often delayed because of low flow in October-November. The upstream schemes contribute to this low flow by upstream diversion of the water. Cropping in the upstream schemes starts as soon as rainfall supplemented with river flow are sufficient to start land preparation and farmers expect that a continued water supply will be available to support the crop.

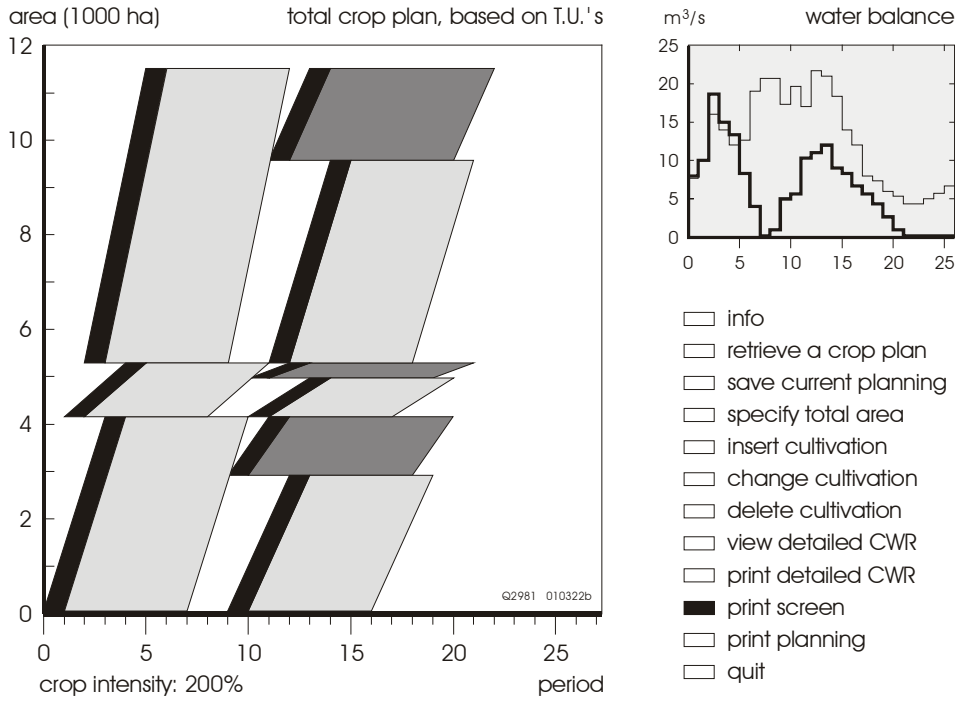

Figure 8.9. On-line design of crop pattern (OMIS screen).

For optimal use of the Cidurian water and minimum losses of agricultural inputs, coordination of the cropping patterns for the total basin is required. Such coordination requires incorporation of all other aspects of water allocation in the basin, i.e. those aspects that are handled in the RIBASIM model. In the next section suggestions are put forward for an integration of the two models to address a basin wide coordination.

8.4 Further integration of planning and operation at scheme (farm) and basin level

The need and potential for water allocation management both at regional and individual scheme level has been illustrated in the previous sections. The observations can be extended to sketch a general multi-sector water allocation problem (Fig. 8.10). The risk of mismatching of available water and actual water demands for such a system is large in view of the different demand locations, return flows, efficient use of a variable river flow and the challenge of coordination of different local operating centers.

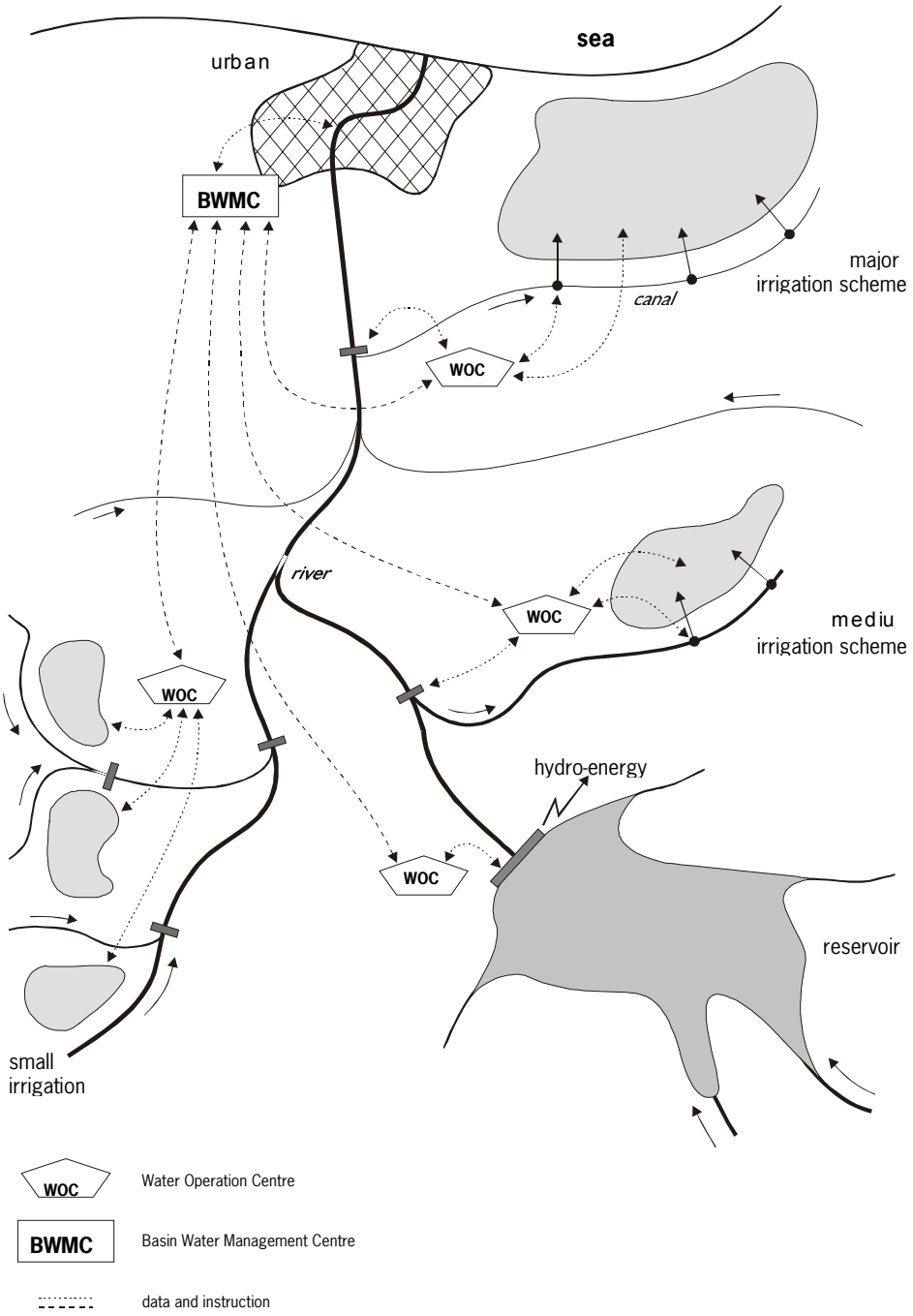

Figure 8.10. Sketch of the multi-sector water allocation problem in a basin.

The goal in water allocation is to maximize the efficiency of overall water use in a basin. Such objective comprises two major steps, viz.:

- planning of water use in a basin such that a maximum use is made of available water (e.g. plan for an adapted farming system which takes best advantage of available water), and
- operational management for a particular planned water use pattern; this concerns real-time guidance to realize the best possible target water use pattern despite variations in the real-time conditions.

Both steps should be supported with a decision support tool, which can handle the large data processing requirements and allows an efficient search for the best solution from many alternatives.

Various components of the RIBASIM and OMIS models can form suitable combinations to provide such tools:

- RIBASIM addresses **planning** at a river basin scale and allows in its input a medium level of detail to address options in agriculture and irrigation practice. A crop-planning tool similar to the one used in OMIS could be added as an additional module to RIBASIM to prepare a crop planning best adapted to the available water. RIBASIM can provide the available water at any point in the network.
- A tool addressing **operational management** for the whole basin could center on the real-time operation module of OMIS. Using the same method as in OMIS, RIBASIM water allocation could be used to allocate water one period at a time making a provisional allocation for each period with predicted inputs (flows) at the relevant points resulting in desired allocations, followed by an allocation using the actual inputs. Monitoring and communication should then be appropriately expanded to encompass the total basin.

8.5 Perspective on regional water resources allocation

The applications to the different basins illustrate the relevance of linking options in agricultural/ irrigation development to the regional water balance. Such options may then relate to different cropping patterns associated with agricultural development as well as technological innovations influencing water use.

It is also demonstrated that realization of a maximum water use efficiency in a river basin is a complex problem involving planning operational management and above all adequate management that needs to be supported by a substantial flow of information. Models like RIBASIM and OMIS are then a necessity to handle this flow of information.

Apart from a straight application of the two models to the respective problems, further progress towards a generally useful decision support package could be made by combining concepts/modules. Two steps can be recognized in such further development:

- improve planning by adding more flexibility to RIBASIM for specifying agricultural/irrigation options, and
- generalization of the operational management from OMIS for application to a complete river basin.

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9. Assessing water-saving systems of rice intensification: economic criteria for farm household evaluation

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9.1 Introduction

Experiments with new systems of rice intensification (SRI) by farmers in Madagascar have shown spectacular results during the last 20 years. By keeping the soil moist, but not inundated, only half as much water would be required as compared to irrigated rice practices, yet grain yields can be substantially raised through better synergistic input interactions (Uphoff, 2001). Moreover, SRI does not necessarily rely on often expensive external inputs: compost can be used instead of chemical fertilizers and simple hand weeding minimizes the use of herbicides. With methane emissions reduced by not inundating rice fields, SRI can claim to be environmentally friendly, water- and capital-saving, and land-augmenting. As can be expected, those savings are achieved by using higher inputs of labor, management and different skills than in conventional practices. The long-term effects of higher yields on soil fertility appear uncertain, a feature not unique though for SRI.

With its strong emphasis on synergistic interactions, the benefits of alternative systems such as SRI tend to be mainly measured in biophysical terms. Repeated trials under different conditions and in different locations invariably constitute the first stage of establishing the exact nature of the benefits promised by new practices. Less attention, certainly initially, tends to be given to the welfare implications in terms of farm household income, consumption and labor use, and to more aggregate effects on prices and markets. However, the potential welfare improvement for households, the nature of exchange configurations, the strength of existing institutions, and the options for policy support are crucial factors in the eventual decision of farmers to adopt a new practice or technology.

To capture the biophysical and socio-economic elements of SRI, we propose the concept of *sustainable agricultural intensification* (SAI). It emphasizes (1) protection of the natural resource base to safeguard soil nutrient stocks and land and water productivity, and (2) efficient combinations of production factors that improve farm household income, including returns to labor. As trade-offs between natural resource use and welfare are likely to arise, we focus our attention primarily on 'win-win' practices that enable a simultaneous improvement on both scores. Notice that the concept of SAI is neutral regarding the particular input(s) which use is (are) intensified.

Based on the concept of SAI, this paper discusses a number of criteria to evaluate ex-ante adoption of SRI by farm households. These criteria are largely based on the likely effect of new practices on the use and return to factors of production such as land, labor and capital. The opportunity cost of using (or freeing) resources for (by) SRI needs to be carefully examined to understand the welfare cost and benefits of adopting SRI by particular households. This is especially relevant for labor. SRI is labor-demanding and will therefore directly compete with other remunerative labor uses, both off- and non-farm. In the presence of important complementarities between labor and other input use, SRI might pose dilemmas for farmers with limited labor-availability. External factors such as imperfectly functioning institutions and markets may also constrain farmers from adopting SRI. At the same time, practices that, explicitly or implicitly, address such constraints (surplus labor in a poorly functioning labor market, liquidity constraints preventing the purchase of external inputs) may encourage adoption.

Finally, as SRI is yield-increasing, price effects may occur that complicate impact assessment for both net buyers and net sellers of rice.

9.2 Evaluation criteria

Conventional methods of irrigated rice production are characterized by embodied technical innovation via improved seeds and agro-chemicals, and public investment in irrigation, extension and other support services. SRI innovations work through synergetic input interactions, which create increasing yield returns within rice crops if all practices are properly synchronized. SRI's expected effects on the farm household can be summarized as follows:

- production : improved yield per unit of land;
- input use : substantial water saving; substitution of compost and hand weeding for herbicides;
- factor use : increased labor use (transplanting, weeding); improved management skills; investment in land preparation (adding to labor demand);
- environment : less water, herbicides, and methane emissions; uncertain effects on nutrient stocks;
- income : change in output net of all input changes (value added);
- expenditures : change in consumption, purchase of inputs, leisure;
- prices : stable or declining, depending on tradability and government policy.

Complicating the estimation of SRI effects is the 'package' nature of its technology. Like in many soil and water conservation (SWC) methods, farmers have the option to select only those practices out of the full set of recommended practices that suit their resource position best. Because of input synergies farmers will fail to realize more than proportional yield increases, which can be rational as long as the value of the resources saved for other purposes outweighs the yield increase. Labor scarcity often motivates such decisions.

SAI implies that farmers attempt to increase returns to scarce factors of production in such a way that the stock and quality of their natural resource base is maintained. While most approaches tend to focus on land and water productivity as major indicators for adoption, far less attention is usually given to returns to labor (Low, 1993). Farmers tend to consider yield increasing and/or cost saving technologies and practices from five different perspectives: (i) profitability, i.e. the possible contributions to household income and consumption, (ii) implications for input efficiency, (iii) consequences for input substitution and labor use, (iv) possibility to manage or reduce risk, and (v) sustainability, i.e. the impact on the natural resource base. We will discuss farm household behavior that guides decision-making procedures regarding these technologies, and derive a number of key principles that enhance their socio-economic attractiveness.

9.2.1 Profitability

New agricultural technologies and practices can only be expected to be adopted when they enable farmers to attain higher and more stable income and consumption opportunities compared to existing technologies. Profitability requires both effective market outlets and favorable output/input price ratios. Market distortions or inefficient exchange networks reduce incentives for investments in new technologies and management practices. Hence, development of new and revision of existing agricultural systems may be hindered and farmers may continue subsistence cropping relying almost exclusively on locally available resources (Low, 1993; Lockeretz, 1989).

Contrary to what is usually expected, farmers are likely to apply externally purchased yield increasing inputs for commercially oriented production activities (Reardon *et al.*, 1999; Putterman, 1995). In the cotton belts of Southern Mali and Burkina Faso, chemical fertilizers, crop residues and animal manure tend to be mainly used for cash crops that guarantee sufficient monetary returns to warrant these costs

(Sissoko, 1998; Savadogo *et al.*, 1998). Similarly, animal traction and improved tillage result in higher returns when applied on fertile fields where commercial crops are grown. In the Central Chiapas region of Mexico, crop residue mulching only appears to be profitable when combined with animal traction in intensive market-oriented cropping activities (Erenstein, 1999).

Farmers' participation in market exchange can be considered a necessary condition for profitable and sustainable agriculture. Involvement in trade provides financial resources for the purchase of inputs and consumption goods. Those households that maintain a net demand position on the food market will benefit from low commodity prices (Budd, 1993; Goetz, 1992). Where access to formal credit services is limited, investments can be financed from income derived from off-farm employment (Ruben & Van den Berg, 1999). Market development could enhance the willingness to invest, while involvement in market exchange generally improves farmers' responsiveness to price incentives. Hence, when market failures prevail, policy reforms remain a first best solution. In their absence, increasing reliance on low external input technologies tends to be the pervasive outcome.

9.2.2 Input efficiency

Prospects for new agricultural technologies and practices finally depend on the possibilities to improve *input efficiency*, i.e. the marginal returns derived from an additional unit of (organic or inorganic) inputs. Production ecological approaches indicate that nutrient uptake efficiency is positively affected by the joined availability of production factors, e.g. nitrogen and phosphorus (Van Keulen, 1982). Substitutes for chemical fertilizers are generally characterized by low recoveries due to immobilization of nutrients and slow decomposition of organic material.

Nutrient recovery and uptake efficiency can be enhanced through (i) SWC measures that improve the soil nutrient retention capacity, and (ii) frequent nutrient applications based on crop requirements during the growing season (e.g. shortly after sowing). Poorly endowed farmers lack mechanization to substitute both labor-demanding activities

Agricultural yields depend on the most limiting factor and can only be increased when input combinations are made available that ensure adequate synergy effects based on *complementarities* between different growth-limiting inputs (i.e. nutrients and water). Studies regarding input efficiency refer to the functional relations between soil carbon content and (in)organic nitrogen supply to prevent immobilization of nutrients, and to the appropriate ratio between nitrogen and phosphorus to guarantee timely organic matter decomposition (Penning de Vries & Van Laar, 1982). This implies that input efficiency tends to be low when complementary inputs are not timely available or in sufficient amounts.

Generally, farmers know how to combine different inputs to generate positive synergy effects. For example, organic and chemical nutrient inputs are no full substitutes, and combinations of locally available resources with selectively applied external inputs often give the best results. In practice, farmers use purchased (chemical) inputs, because they allow timely application, reduce the demand for labor in critical periods, have a guaranteed and known quality, and contribute to a better appearance of the produce (product quality) in the marketplace. Given the often low nutrient content and uncontrolled nutrient availability from organic fertilizers (green manure, mulch, dung, compost), use of chemical fertilizers cannot completely be abandoned.

9.2.3 Factor substitution

Most analyses of new agricultural technologies and practices consider only short- or long-term yield effects, but do not give any indication of labor requirements and returns to labor. Implicitly, family labor is thus considered an 'abundant' resource. While technical efficiency is usually evaluated against

the background of most limiting factor for yield increase (i.e. water, nutrients, energy, pests and diseases), economic efficiency should be based on an analysis of critical factors that determine farm household income (land, labor, capital, knowledge). Moreover, certain limitations regarding the possibilities of substituting external inputs by labor should be recognized.

New technologies, e.g. soil conservation practices, require much labor. Physical soil conservation measures promoted in the Central American hillsides and West African lowlands have resulted in only small yield increases, but require large amounts of labor for construction and maintenance and involve substantial costs for the purchase and transport of materials (Stocking & Abel, 1989). For a systematic evaluation of the attractiveness of such practices from the farm household perspective, returns to land and labor need to be compared simultaneously (Reardon, 1995). Particularly, *marginal* returns are important and they need to be compared to other activities (i.e. off-farm employment; hiring-out of land). Even when new practices can improve nutrient and soil organic matter stocks, the short-term improvement in yield is usually small compared to the additional input requirements, especially labor. Consequently, returns to labor tend to be higher for technologies that maintain some external inputs to guarantee input complementarities.

Fig. 9.1 provides an overview of a number of agricultural technologies and practices, taking into account expected yield effects and labor requirements. The final selection of these practices made by the farmer is likely to depend on the labor/output price relationship. Soil-fertility-enhancing measures give favorable results on both yield, and labor requirements, followed by mixed cropping and minimum tillage. SWC measures and intensive weeding are attractive for cropping activities with a high value added and in situations where labor costs are relatively low.

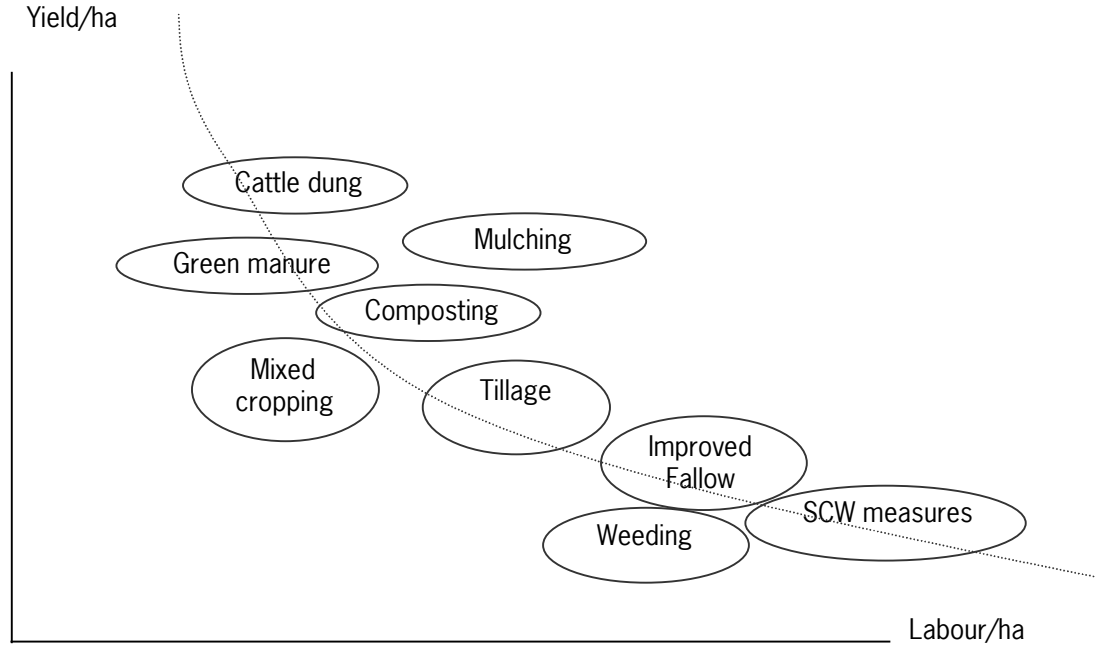

Figure 9.1. Factor intensity and yield effects of a number of agricultural technologies and practices.

The high labor requirements of most new practices can be considered as major limiting factor for adoption. Labor tends to be scarce in semi-arid areas during the periods of soil preparation, weeding and harvesting (Fafchamps, 1993) and competition for labor occurs when mulching, manuring or crop residue recycling are introduced. Otherwise, resource-poor farmers are likely to earn part of their income from off-farm activities that have to be reduced when labor demanding technologies are

introduced (so-called labor-led intensification, see Reardon *et al.*, 1988). Farmers are likely to adjust their production system only when the additional income as a result of such technologies favorably compares to labor's opportunity cost. Some practices, e.g. physical soil conservation measures, can be executed in off-season periods, but require leisure time that may be reserved for social or communal purposes.

9.2.4 Risk management

Resource-poor farmers often rely on fairly diversified patterns of activities to reduce and manage risk . Diversification of crop and livestock production and their integration with (agro)forestry, aquaculture and improved fallow practices could reinforce the resilience of farming systems through processes of nutrient recycling, biodiversity management and integrated pests and disease control (Muller-Samann & Kotschi, 1994). Consequently, yield levels may be more stable and dependency on purchased inputs can be reduced.

Risk management can also take place through farmers' participation in off-farm and non-farm activities (Reardon *et al.*, 1994). The revenue earned with such activities depends less on variable weather conditions and thus provide an adequate insurance against co-variate shocks (Udry, 1990). Besides crop diversification, participation in non-agricultural activities is therefore a suitable manner to manage risk. Reliance on this strategy becomes feasible when labor demand for agricultural activities can be reduced, and household members possess sufficient skills and knowledge for wage labor or self-employment (Reardon, 1997).

Another issue related to short-term risk management refers to the farmers' capacity to adjust input use under changing weather or environmental conditions. Adoption behavior strongly depends on the learning capacity that enables prompt reactions to unexpected events (Fujisaka, 1994). Although many agricultural technologies and practices have been developed through participatory and horizontal extension methods (e.g. farmer to farmer approach; farmer field schools), there is a rather weak understanding of the dynamics of production systems. For example, the rejection of maize-cover crop systems in Honduras due to inadequate control of weeds. Subsequently, associated technologies like living fences, contour cropping, and crop residue recycling were abandoned (Neil & Lee, 2000).

9.2.5 Sustainability

SAI implies that the production capacity of the resource base can be maintained in the long run. This does not necessarily mean that at each moment in time the natural resource base should be maintained. Farmers may deplete resources in the short term while investing in its recovery in subsequent periods. This concept is also known as '*weak*' *sustainability* (Pearce & Turner, 1990) and is often applied in the economic analyses of land use systems.

Farmers' preference to deplete resources in the short term can be explained from a trade-off perspective. For comparison of current and future costs and benefits, discounting procedures are often used that reflect farmers' relative time preference. People facing more risk tend to maintain a high discount rate, reflecting their preferences for immediate revenues. Long-term investments are especially sensitive to high discount rates, as Current *et al.* (1995) demonstrated for agroforestry projects.

A second type of trade-off occurs when farmers assess the welfare and sustainability implications of alternative technologies (Kruseman, 2000). Farmers' adoption of new practices can only be expected when they generate positive welfare effects. In practice, however, such practices frequently imply a sacrifice in terms of income or consumption objectives. Moreover, production systems may be sustainable at lower system levels (field, farm), but can still cause unfavorable externalities at higher

system levels (village, region). In such cases, (agrarian) policy instruments can be helpful to overcome trade-offs and suitable incentives should be identified that permit a simultaneous improvement of welfare and sustainability ('win-win' scenarios; Kuyvenhoven *et al.*, 1998).

9.3 Evaluation methods

Empirical studies on the efficiency of new practices and technologies tend to focus on yields and effects on the resource base. Positive returns to land usually indicate their financial feasibility. However, an economic evaluation of their attractiveness from a farm household perspective requires that additional criteria have to be taken into account (Table 9.1). Based on the five criteria that are important in the socio-economic appraisal of agricultural technologies and production systems, different analytical methods can be used (Ruben *et al.*, 2000).

Table 9.1. Analytical procedures for the appraisal of new technologies and practices.

Criterion	Analytical procedure
Profitability	Partial Farm Budgets and Cost-Benefit Analysis
Input efficiency	Production Functions
Factor substitution	Farm Household Modeling
Risk	Portfolio Analysis
Sustainability	Bio-economic Modeling

The profitability of agricultural technologies can be measured in a rather straightforward manner, making use of conventional *cost-benefit analysis* (CBA). Though profitability is a necessary condition for adoption, it does not take into account non-income farm household objectives. CBA provides an appraisal of average costs and revenues at prevailing prices, usually in a partial equilibrium framework. It is usually applied for the appraisal of specific practices, like SWC (De Graaff, 1996; Lutz *et al.*, 1994), crop residue mulching (Erenstein, 1999), or agroforestry systems (Current *et al.*, 1995). Other than income objectives can be taken into account by extending CBA into *multi-criteria analysis* (MCA) (Van Pelt & Kuyvenhoven, 1994), however, it remains a tool for partial analysis only.

For a thorough appraisal of input efficiency, information regarding marginal returns to factors of production is required. Therefore, *production function analysis* (PFA) provides a useful analytical framework (Heerink & Ruben, 1996; Mausolff & Farber, 1995). PFA can be used to estimate marginal returns to land and labor for new and conventional production technologies, and enables to identify the range of input-output price ratios where conversion is likely to take place. Moreover, typical farm household characteristics important for adoption of new technologies can be identified.

Full analysis of the economic attractiveness of technologies taking into account factor substitution requires *farm household modeling* (FHM) (Singh *et al.*, 1986). Farm household models explicitly consider complementarities between inputs and provide an analytical framework for simultaneous evaluation of production and substitution effects. Moreover, differences in supply response between tradable and non-tradable commodities are recognized (De Janvry *et al.*, 1991). Further extensions towards village-wide models also include market linkages and general equilibrium effects (Taylor & Adelman, 1996). FHM offers useful procedures for policy simulation, assessing farmers' supply response to different types of economic incentives.

Aspects of risk management can be included in programming models and econometric procedures. However, explicit appraisal of farmers' risk behavior and coping strategies requires a separate analysis. Therefore*, portfolio analysis (PA)* can be used to assess the variability amongst different household income categories (farm, off-farm, non-farm) and to identify major strategies for consumption smoothing (Deaton, 1992). Hence, PA takes linkages with non-agricultural sector, and differences in supply response between food deficit and food surplus households into account.

Finally, for a comprehensive analysis of the sustainability implications of technologies*, bio-economic modeling* (BEM) is suitable. BEM enables an appraisal of both current and new technologies and their contribution to farmers' welfare and their effect on the natural resource base (Kruseman & Bade, 1998; Barbier & Bergeron, 1998; Deybe, 1994). Trade-offs between both objectives can be established, and policy instruments to enhance the adoption of new practices can be identified.

9.4 Research issues

Once the technical characteristics of SRI practices have been established and scores on the evaluation criteria are satisfactory, constraints should be addressed and incentives identified to stimulate adoption. Adoption has general features which can be addressed through generic policies and effective institutions (Table 9.2).

Table 9.2. Policy instruments for SRI practices.

Criterion	Policy instruments	Implications
Profitability	Input costs; market prices Infrastructure investment	Higher average returns Market development (lower transaction costs)
Input efficiency	Relative prices Training and extension	Higher marginal returns Access to knowledge and information
Factor substitution	Rural financial systems Social capital	Access to finance Resource sharing
Risk management	Price stabilization Off-farm wages Education	Stable returns Income diversification (smoothing) Willingness to invest
Sustainability	Property rights	Collateral for lending Income certainty

It is well known that a number of *individual factors* influence adoption behavior. New agricultural technologies tend to be adopted earlier and more frequently by farm households that have better access to land and capital resources and that are more involved in market exchange (Feder *et al.*, 1985). Moreover, factors like age, education and gender also influence farmers' willingness to invest. New technologies and practices are likely to be adopted by subsistence-oriented, medium-size farmers in remote regions where opportunity costs are usually low. Adoption of labor-demanding technologies by small and marginal farm households faces, however, major constraints due to their usual high participation in off-farm employment. Such technologies can only contribute to poverty alleviation when returns to land and labor simultaneously increase. Therefore, agrarian policies should provide incentives that guarantee both farmers' welfare and maintenance of the resource base.

Nowak (1992) has emphasized the distinction between inability and unwillingness to adopt. The latter is related to information and risk problems, expected unfavorable performances under specific or prevailing conditions, and outspoken preferences for other options. The inability-to-adopt factors largely overlap with the criteria in this paper, and would therefore be partly amenable to policy interventions. Nowak identifies the following factors related to inability on the side of the farmer:

- information lacking or scarce;
- costs of obtaining information too high;
- complexity of the system too great;
- too expensive;
- labor requirements too high;
- planning horizon too short (benefits too far in the future);
- limited availability and accessibility of supporting resources;
- inadequate managerial skills; and
- little or no control over the adoption decision.

Although in an entirely different setting, a recent USDA study of adoption of technologies and practices related to four key management categories: nutrients, pests, soil and water by farmers in 12 watersheds in the United States, adds interesting information (Caswell *et al.*, 2001, p. iv):

- An operator's education had a significantly positive effect on his or her adoption of information-intensive technologies, such as the use of biological pest control or nitrogen testing. The increasing complexity of new technologies needs to be considered by agencies or technology providers when targeting potential users.
- Technical assistance, demonstration, or consulting services may be necessary to promote adoption of new practices.
- Land ownership had less impact on adoption than initially expected – probably because most of the practices included in this study were not structural.
- The combined-area models represent an aggregation across very distinct watersheds. Results of such models can be misleading for policy makers since important information can be 'lost' in the process of aggregation. Adoption incentives developed to address factors identified in the aggregate model may be appropriate for only one area and counterproductive for all others. While this 'averaging problem' exists for most policies, comparison of the combined-area models presented illustrates the magnitude of differences between the watersheds.

9.5 Information requirements

To satisfy the conditions for adopting SRI by farmers, the profitability of the farming system applying such new practices should be determined. As a first approach, single farm budget analysis suffices, but a more complete cost-benefit analysis gives a better understanding of the profitability of SRI and its adoption.

Because of the crucial role of synergistic interaction among inputs, a careful analysis of input efficiency with and without adoption of SRI is warranted. In this way the changes in returns to various production factors can be determined and compared with their opportunity costs. Production function analysis can provide this information.

Adoption of SRI is likely to be influenced by policies and institutions that could lessen constraints related to the specific resource position of farmers, or to the socio-economic and institutional context in which they operate. To establish the effectiveness of supporting interventions, analysis of the farm household's response to policies is helpful in understanding which factors, in a specific (regional) context, limit adoption most. For such an exercise, farm household (bio-economic) modeling is a powerful tool of analysis.

In general terms, application of these analytical techniques requires the following information.

General criteria:
- sample frame selection (with/without the intervention);
- minimal sample size (for regression analysis);
- farm household stratification (by major type);
- data collection intervals (timing of seasonal input demand).

Specific data:
- farm characteristics (farm size, number of plots, soil quality, tenancy status, SWC investments);
- family characteristics (family size, age, education, gender, off/non-farm employment);
- production systems (cropping & livestock activities, input use, water use, labor requirements, marketing, input and output farm-gate prices);
- consumption systems (total income, income composition, food and non-food expenditures, savings);
- external relations (access to finance, common resource areas, technical assistance, extension, local institutions, quota regimes, taxes and fees).

9.6 Expected results

At this stage, we can only speculate about the conditions under which adoption of SRI will be most successful. The possibility of partial adoption of the different practices that constitute SRI makes an overall assessment even more difficult. Taking into account the factor proportions of several of the contributing elements of SRI (SWC, weeding, composting), working capital, labor requirements, management skills and well-organized information flows appear to be critical success factors. The following research questions are therefore important:
- Are the regions commercially integrated with other markets (i.e. low transaction costs)?
- Are most of the adopting farmers net sellers (i.e. surplus farmers)?
- Can investments in SWC be financed from revenues of off-farm employment?
- How relate required management skills to farmers' education and experience?
- Are there efficient water pricing regimes?
- What has been the effect of market liberalization in the past on external prices?
- What mechanisms exist to cope with the new risk pattern?
- Is there surplus labor? How is the labor market functioning?
- Can labor-demanding practices of SRI be substituted by external inputs?

9.7 Acknowledgements

Sections 9.2 and 9.3 draw heavily on parts of the authors' contribution to Norman Uphoff (ed.), *Agroecological Innovations*, 'Economic Conditions for Sustainable Agricultural Intensification' (Chapter 5), forthcoming, 2001.

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10. Research goals and priorities

The goals of the inception workshop can be summarized as:
- To discuss the state of the art with respect to water-saving rice systems and to exchange knowledge about such systems.
- To exchange knowledge about tools enabling the analysis of the impact of water-saving rice systems at various scale levels (field, farm and region).
- To identify feasible research goals.
- To define a research program for the year 2001 and beyond that contributes to the realization of these goals.

The first two objectives of the workshop were especially dealt with in the preceding Chapters. Different contributions to this workshop (e.g. Chapter 4, 5 and 7) showed that it is possible to realize rice yields with water-saving techniques equivalent to or higher than yields from conventional flooding systems. However, no systematic research has been done to understand the performance of water-saving systems, to examine overall resource use, to estimate the overall water-saving and to stimulate adoption of such systems. Latter two points were emphasized by other contributions to the workshop (e.g. Chapter 8 and 9): the need to design water-saving rice production systems at different scales and in an integrated way so that systems can meet various objectives. Tools and operational frameworks were presented that enable to study the agro-technological, environmental and socio-economics dimensions of new water-saving systems at different scales. Such frameworks are required to answer interrelated research questions and to enable multidisciplinary research. Only the joined effort of different disciplines, such as plant, environmental and social sciences, in the design of water-saving systems at different scales enables the development of novel systems that are technically feasible, socio-economically viable and environmentally sound.
The last two objectives of this inception workshop were dealt with during a concluding round-table discussion, which is briefly summarized in this Chapter.

10.1 Goals

The overall objective of the project is to design and demonstrate successful water-saving rice production systems in four rice-growing areas: China, India, Indonesia and Madagascar, and to analyze their impact on farm households and regional hydrology.

To realize this objective three project goals were identified during the workshop:
1. Evaluate whether water, land and labor productivity can be increased simultaneously in water-saving rice production systems.
2. Demonstrate the benefits of such systems to resource-poor farmers.
3. Quantify the potential regional water savings and reallocation options compared to other options.

10.2 How?

To realize these goals, the participants of the workshop agreed to subdivide the work into a research and demonstration component. During the workshop, a range of research topics were identified that are of relevance for the development of water-saving rice systems. Because of the wide variety of research issues identified and limited funding, each participant will not be able to contribute to all issues. The issues to be dealt with by each participant should relate to their regional interests/problems and current research programs. Within the experimental layouts, common observations have to be made to allow comparison among locations. The following research issues were identified:

1. The effect of weeding/aeration – The hypothesis is that weeding or loosening of the topsoil improves aeration, which may increase root growth as found in SRI systems in Madagascar which may (partly) explain the high yield performance of these systems.
2. Biological nitrogen fixation – The intermitting wetting and drying of the soil may improve the conditions for biological nitrogen fixation. Knowledge on this topic scarce. Empirical evidence is difficult to obtain and the issue has most probably a location-specific component.
3. Transplanting effects – This issue involves several related topics that all seem to affect sink-source relationships in the growing season. The age of the seedlings at transplanting may have an impact on the number of tillers to be produced. The way of sowing/planting (transplanting, direct sowing, throwing, etc.) should be investigated to identify which method gives best results under water-saving conditions.
4. Crop establishment - Planting density may be of importance for root and crop growth and for the possibility to carry out mechanical weeding operations.
5. Cultivars – Some cultivars have more drought resistance than others. In some regions drought-resistant cultivars are already identified, in other regions such cultivars still have to be identified. Short growth cultivars may also use less water and combined with drought resistance such cultivars may be suitable for water-saving conditions.
6. Nutrient management – Most likely, nutrient dynamics under water-saving conditions will be different from the standard flooding practices. Knowledge about the nutrient dynamics under water-saving conditions is lacking.
7. Water-savings at regional level – What is the significance of water-saving rice production at the field level for the regional scale? Water-savings at the field level may not necessarily contribute to increased water availability in other sectors and regions due to imperfections in distribution or timely availability. This issue involves the upscaling of systems at field level and to identify benefits and/or problems at regional scale.
8. Policy options – What is the likelihood that farmers adopt water-saving practices? Adoption is most likely affected by the effect of such practices on the income position of farmers. Farm household models incorporating socio-economic characteristics and technical characteristics of the water-saving production systems may help to identify the conditions under which these systems are adopted and adapted by farmers to better fit their conditions.
9. Water quality and other side effects – What are the effects of water-saving techniques on water quality? For example, are pesticide and nutrient concentrations in drained water likely to increase using such techniques. Do such concentrations pose off-site problems?

Biophysical research issues 1 to 6 all affect water, land and labor productivity of water-saving rice production systems and thus are closely related to the realization of goal no. 1. Research issue 7 relates to goal no. 3, while research issue 8 relates to goal no. 2. Research issue 9 is of general importance and can be considered a boundary condition that is relevant for the realization of all three goals.

The following issues were considered of relevance with respect to the demonstration component of water-saving rice production systems:

1. Demonstration of water-saving rice production in contrasting agro-ecological and socio-economic environments.
2. Link demonstrations to current regional research efforts.
3. Raising awareness.
4. Evaluation at the farm level.

The demonstration component of the project should not be limited to an illustration of the technical feasibility of water-saving techniques but should also include an analysis of the socio-economic conditions under which technical innovations are adopted. Demonstration of the socio-economic viability of water-saving rice systems is, therefore, closely related to research issue 8.

10.3 Where?

The experiments and demonstration trials will be carried out at the following locations:

- China: Jiangxi and Jiangsu province.
- India: State of Tamil Nadu.
- Indonesia: Riau province (West Sumatra) and Sukamandi (West Java).
- Madagascar: low and high plateau.

10.4 Output

The project will generate the following main output:

- Consolidation of current, and generation of new knowledge on water-saving rice production systems that enables to identify the potentials of such systems for different agro-ecological and socio-economic conditions.
- Capacity building and exchange of knowledge both between North-South and South-South. MSc and PhD students are part of the project. Young scientists from developing countries will be trained to analyze and integrate different types of knowledge with respect to rice production systems.
- New information on water-saving rice production that increases awareness among various stakeholders (from farmers to local policy makers) and that contributes to the international debate on water for food.

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