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Rice cropping systems and resource efficiency

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ANOVA	Analysis of variance
ATT	Average treatment effect on treated
ATU	Average treatment effect on untreated
AWD	Alternate wetting and drying
BF	Basal fertilizer
BMP	Best management practice = RMP
CDF	Cumulative distribution function
CRN	Controlled released nitrogen management
DAT	Days after transplanting
DS	Dry season
DSP	Direct seeding practice
ER	Effective rainfall
ET	Evapotranspiration
FAP	Farmers' adapted practice
FFP	Farmers' fertilization practice
FI	Flooded irrigation
IP	Total water input = WC
IR	In Xu et al. (2012): Irrigation water, in Boumann et al. (2005): total water input: Irrigation plus rainfall
IRRI	International Rice Research Institute
LSD	Least significant difference
MJ	Megajoule = 1 million Joule
NH_3	Ammonia
PF	Panicle fertilizer
PL	Percolation losses
ps-d	person days
RMP	Recommended Management practice = BMP
SD	Standard deviation
SNS	Submerged non-submerged irrigation
SRI	System of rice intensification
SSF	Strong seedling fertilizer
SSNM	Site specific nutrient management
TF	Tillering fertilizer
VMP	Versatile multi-crop planter
WC	Water consumption = IP
WP	Water productivity =WUE
WS	Wet season
WUE	Water use efficiency = WP

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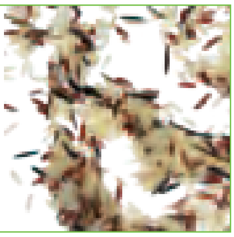

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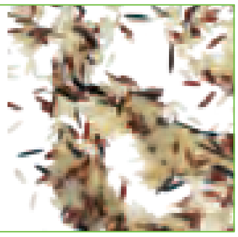

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Foreword

One of the major challenges in the world today is providing food security for around seven billion people. Nor does the challenge end here. It is estimated that the world's population could increase to nearly nine billion by the middle of this century. This impending scenario demands dramatically improved resource efficiency in agricultural production.

The most important resources for food production - arable land, water and energy - are interlinked in a multitude of dependencies. Different sectors constantly compete for their use. Agriculture, as the largest user of natural resources, offers also the greatest opportunities to preserve resources by improving resource efficiency.

New agricultural technologies are needed to reach dual, but potentially conflicting, goals: conserving natural resources and providing food for an increasing demand. Are we prepared to take on this challenge? What is the current state of knowledge in the field of resource efficiency in today's food production systems? And will emerging resource efficient technologies be adopted by the farmers?

Rice is one of the world's most important staple crops. The following study provides an overview of major rice production systems and their technologies. It analyses the different degrees of consumption of resources such as water, energy, fertile land, labor and inputs of fertilizer and pesticides. The study also looks into the contribution of these production systems to food security, as well as the effects of rice production on climate change. Incentives relevant to farmers for the adoption and diffusion of innovative production systems are also considered.

This desk-study draws on results of international agricultural research as well as on the ground experiences of GIZ and other international development organisations.

The engagement of the German Federal Ministry for Economic Cooperation and Development (BMZ) to finance this study not only allows an interesting overview on resource use efficiencies in rice production but also provides unexpected insights into the farmer's rationale in their decision making. Trusting that this study will contribute to a better understanding of how to improve resource efficiencies in rice production, I wish all a fruitful reading.

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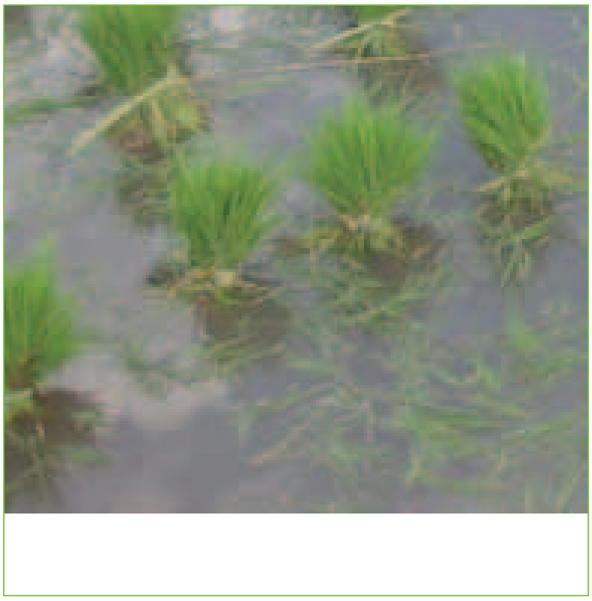
0 Abstract

Globally, rice is the most important staple crop and therefore crucial for food security. An estimated area of 15–20 million hectares of irrigated rice will face water scarcity, threatening the livelihoods of many small scale farmers with land holdings of less than three hectares. Different water saving rice cropping methods have been developed, but their broader ecologic and socio-economic outcomes remain unclear. Therefore, the present study reviews the scientific literature and compiles findings that contribute to fill the knowledge gap on input use and environmental and socio-economic outcomes of selected water saving rice cropping systems.

Research results show a broad range of possible water savings and conflicting figures on changes in water use efficiency. Results appear to be site specific and affected by seasonal variation. The existence and control of irrigation systems in terms of irrigation amount and timing by individual farmers is crucial for the success of water saving rice production. Different yield levels (worldwide ranging from less than 1 t/ha to up to 10 t/ha) make generalizations on energy input to output ratios difficult. There seems to be agreement that rice cropping without puddling uses significantly less energy compared to conventional wet soil cultivation and more aerobic conditions will change the mechanization possibilities in rice cultivation. Labor requirements vary largely in different locations (25 to 275 person days for conventionally flooded rice). Different methods for transplanting rice exist some of which are more time consuming than others. The initially increased time for transplanting in the System of Rice Intensification (SRI) is reported to decrease with more experience. However farmers have labor bottlenecks due to other on farm or off-farm activities. The adoption of water saving technologies seems to change the gender involvement in rice cropping. All rice cropping systems respond positively on the application of mineral fertilizer. Integrated organic and mineral fertilizer applications have a positive effect on soil quality. However, farmers might prefer to apply organic matter to higher value crops. In general, high water levels effectively control most weeds of rice. Increased weed occurrence is a major problem under aerobic culture. However, no differences in weed biomass comparing SRI with recommended management practices are frequently reported. In the absence of mechanical options to control weeds, pesticide applications may significantly affect rice yields under SRI while pesticide applications do not affect conventional yields. However, whether farmers resort to pesticide depends on the pesticide price, the availability of sufficient amounts of pesticides in a timely manner and the existence of functioning local financial



markets to provide credit. Grain yields under different rice cropping systems vary largely due to site specific conditions and different cultivars. In general, results show that the same yield can be achieved with less seed and less water and that SRI, Alternate Wetting and Drying (AWD), and other improved methods outperform farmers' practices. Ammonia volatilization is affected by climatic conditions, type of nitrogen fertilizer application, and field water management. Experiments show that the type of N fertilizer dominates ammonia volatilization compared to water depth. Also water depth has no significant influence on total N loss from the rice field. Repeated wetting and drying increases soil pore volume, and repeated application of organic matter, as practiced in SRI, increases total soil C and N contents, and soil microbial biomass, hence improving soil quality. Farmers' top most constraints for adopting water saving technologies are (1) difficulties in land leveling, (2) difficulties in water control and management, and (3) shortages in labor availability. Farmers have no incentive to save water where irrigation water and electricity for pumping water are available free of charge. Economic impacts of SRI adoption are very context specific and depend on micro-level socioeconomic and agroecological conditions.

It can be concluded that circumstances affecting the required inputs and outcomes that can be expected under different water saving technologies are complex and highly site specific. The judgment on the overall performance of a water saving technology depends on the chosen reference base. Adapting suitable agronomic practices to local conditions in collaboration with farmers proved to be the most successful option for improving rice cropping in terms of yields, water savings and other input use. Breeding for early vigor and shorter growth duration can produce cultivars that perform better under water saving technologies. The development or adaptation of mechanical weeding devices would help resolve the increased weed infestation in more aerobic rice systems.

1 Introduction, scope and objectives of the study

The agricultural sector has seen considerable growth in the past, mainly brought about by the so called 'Green Revolution' that introduced new technologies like high yielding varieties, mineral fertilizer and pesticides during the 1960s in many countries of the world. Part of the resulting agricultural production increase during that time can be attributed to the expansion of the irrigated land area (De Fraiture et al. 2010).

During the past 50 years, the irrigated agricultural area has more than doubled[1] (FAO 2011) (Figure 1). However, the modernization of agriculture has led to some negative environmental impacts and benefits have been distributed inequitably among countries and people.

Today, the world faces challenges that are different from the ones 60 years ago. Further increases of agricultural production are urgently needed to meet the growing demand of a world population that is predicted to reach about 9 billion by 2050 (FAO 2011). At the same time, persistent poverty and malnutrition, changing diets of large parts of the world's population, the increasing migration and urbanization leading to a stronger competition between rural areas and cities for water, increasing water scarcity, climate change, the increasing role of bio-fuel production in agriculture, and the need for environmental restoration in some areas have to be taken into consideration (De Fraiture et al. 2010). The competition for water, particularly between urban and rural areas has resulted in

[1] For an overview on irrigated area per continent and region, see Table 21 in the Annex, chapter 7.

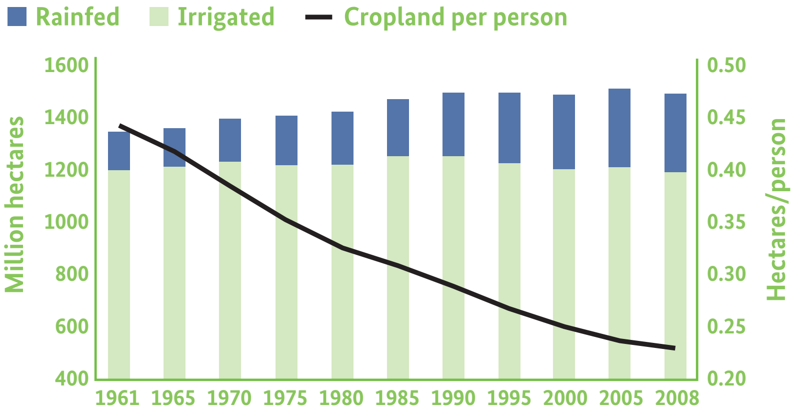


Figure 1 Evolution of land under irrigated and rainfed cropping (1961 – 2008).

Source: FAO (2011)

a situation where about 40 % of the world's rural population live under water scarcity already today.

The challenge to meet the global food demand under the circumstances described above is hence a matter of "seeking the optimal balance between productivity gains and environmental costs. [...] We must consider the farm-level and societal costs and benefits, and we must evaluate inevitable tradeoffs" when searching for optimal solutions (De Fraiture et al. 2010, p.498).

Globally, paddy is the most important staple crop providing 532 million tonnes of food rice to the world's population (Table 1). Although in terms of total production maize and wheat are more important, large amounts of these cereals are not used for human consumption. Humans consume on average about 80 kg of rice, 66 kg of wheat and only 17 kg of maize per capita and year (FAOSTAT 2013).

About 90 % of the world rice production originates from Asia (almost 640 million tons) (IRRI 2013). Latin America produces approximately 25 million tons and sub-Saharan Africa about 19 million tons. In Asia and sub-Saharan Africa, virtually all rice is cultivated by small-scale farmers on land holdings of 0.5 – 3 hectares (IRRI 2013). In many rice cropping areas, two rice crops per year are grown as monoculture. Short crop rotations with wheat are practiced on 15 – 20 mio. ha of rice-wheat systems (Bouman et al. 2006).

Although the world rice production continues to increase, the per capita calorie supply from rice is stagnating since the mid 1980s (Figure 2).

Table 1 Global production and food supply quantity of rice, wheat and maize in 2009

	Production (mio tonnes)	Food supply quantity (mio tonnes)	Food supply quantity (kg/capita/yr)	Food supply quantity (g/capita/day)
Rice, paddy	685.09	531.64	79.9	219
Wheat	686.79	439.42	66	181
Maize	820.54	113.98	17.1	47

Source: FAOSTAT 2013

At present, irrigated rice obtains approximately 40 % of the global irrigation water and 30 % of all developed freshwater resources (IRRI 2013). The sustainability of irrigated rice-based cropping systems seems to be threatened by deceasing availability of irrigation water as well as decreasing water quality (Tuong and Bouman 2003). Water scarcity will affect an estimated area of 15 – 20 million hectares of irrigated rice by 2025 (Bouman and Lampayan 2009).

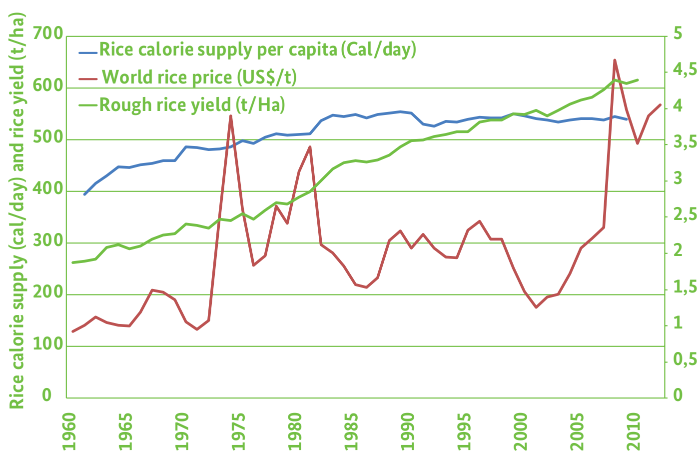


Figure 2 Global rice production, per capita calorie supply, and rice price development between 1960 and 2012.

Source: FAOSTAT (2013)

Different methods of rice crop cultivation that can help reduce the water used for cultivation have been developed like the System of Rice Intensification (SRI), Alternate Wetting and Drying (AWD), dry seeded rice or aerobic rice. However, the broader ecologic and socio-economic effects of these water saving technologies remain unclear. How do water saving technologies affect ammonia volatilization? What are the fertilizer requirements? More weeds will occur in more aerobic systems. Will farmers respond to this by increasing herbicide applications or through increased mechanization (energy requirements) or manual weeding (labor requirement)? How time consuming are water saving technologies for planting and weeding? What is the impact on the environment (ecosystem services)? Under which topographic, climatic and soil conditions can water be saved successfully? And what type of farmer can benefit from water saving technologies (small-scale or larger scale commercial)?

The present study therefore reviews the available scientific literature and compiles findings that contribute to fill the knowledge gap on input use and environmental and socio-economic outcomes of selected rice cropping systems. Since almost all rice production in Sub-Saharan Africa and Asia originates from small-scale farms, the present review focuses on effects within these farming systems.

Conclusions will be drawn and recommendations will be formulated in view of future development initiatives on rice production.

2 Rice production and different rice cropping systems

Rice is produced in a large diversity of agroecological systems. Conen et al. (2010) (Conen et al. 2010) classify the world's rice cropping systems according to the ecosystems in which they are implemented and according to their flooding patterns (Figure 3).

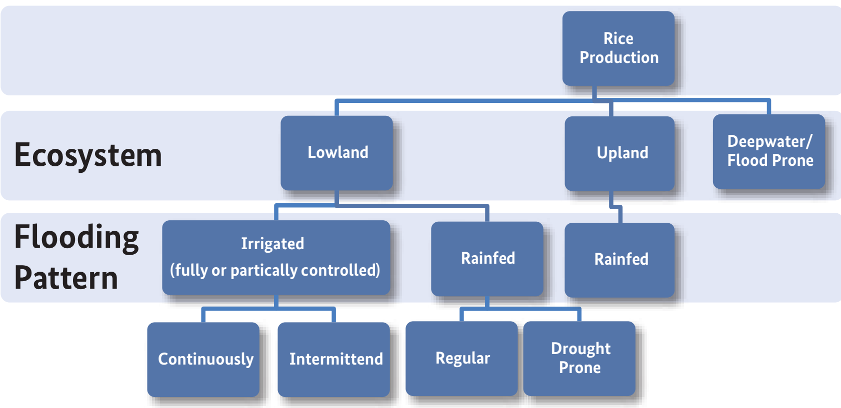


Figure 3 Classification of the world's rice cropping systems.

Source: adapted from Conen et al. (2010); Bouman et al. (2006)

Irrigated lowlands occupy 79 million hectares (mio ha) worldwide and account for 75 % of the world rice production. Irrigated lowland cultivation is the most important rice cropping system for food security (IRRI 2013). Global rice yields range from less that 1 t per hectare (t/ha) from poor rainfed cropping systems to as much as 10 t/ha from irrigated and intensive temperate region rice cultivation (IRRI 2013). The world average of yields from irrigated lowlands is 5.4 t/ha, in Asia alone the average yield is between 3 and 9 t/ha (Table 2) (Bouman et al. 2007; IRRI 2013). For a detailed characterization of the different rice cropping systems, see Bouman et al. (2007).

The following paragraphs give an introduction to the agronomic principles of conventional irrigated lowland rice cultivation, the System of Rice Intensification, Alternate Wetting and Drying, and aerobic rice systems. Other water saving practices include flush irrigation (the crop is irrigated when leaves start to roll) and raised bed cultivation (the crop is irrigated when the water in the furrows between raised beds has disappeared) (Belder et al. 2005).

Table 2 World rice production

Agro environment	World area coverage (mio ha)	World average rice yield (t/ha)	World rice production (%)
Irrigated lowlands	79	5.4	75
Rainfed lowlands	54	2.3	19
Rainfed uplands	14	1	4
Flooded area	11	1.5	No data available

Source: Bouman et al. (2007); IRRI (2013)

Xu et al. (2012) give an overview of other irrigation practices that increase water use efficiency. They are non-flooding controlled irrigation, saturated soil culture, and ground cover systems. However, the latter mentioned irrigation techniques will not be considered in this study. Also, this study does not discuss differences between the systems of traditionally grown rice with full or partial water control, floating rice or recession cultivation.

2.1. Conventional irrigated lowland rice cultivation [2]

Traditionally, irrigated lowland rice is grown in bunded fields that are flooded for most of the cropping cycle. Land preparation mainly consists of tillage, the so called puddling and land leveling. Puddling destroys the soil structure under saturated soil moisture conditions and creates an impermeable soil layer, the so called hard pan that helps reducing water losses through percolation. Puddling helps weed control, land leveling and transplanting (Bouman et al. 2006). Land leveling assures an even distribution of irrigation water to all parts of the field and saves the amount of irrigation water required to achieve this. Rice can either be transplanted into the field or directly seeded. Transplanting is the most common crop establishment technique. Seedlings are grown in a nursery for 20 to 80 days before they are relocated into the flooded field either manually or mechanically. Rice is a crop that thrives well in flooded ecosystems where other terrestrial plants cannot survive. Through this adaptation to unaerobic soil conditions, it is very sensitive to water shortages resulting in symptoms of water stress when soil water content drops below saturation. Therefore, farmers usually maintain their rice field flooded with a water layer of 5 – 10 cm during the cropping cycle until several days before harvesting (Bouman et al. 2006). Typical daily rates of water input throughout the cropping season in tropical lowland rice production are shown in Table 22 in the Annex.

2.2. System of Rice Intensification (SRI)

The System of Rice Intensification (SRI) originally called ‘Système de Riziculture Intensive’ was developed in Madagascar by de Laulanié in the 1980s. SRI is a rice cropping system that is commonly based on six principles and associated practices: 1) start with young seedlings (at the 2-3 leaf stage) (although direct-seeding is also possible), 2) avoid trauma to the roots (gentle removal from seed beds, quick transplanting within 15 – 30 minutes, shallow planting and taking care not to invert the root tips), 3) reduce plant density (plant single plants per hill at 25x25 cm depending on soil quality (wider in high quality soils), square planting), 4) avoid continuous flooding (giving just enough water on a regular basis with dry intervals, maintain mainly moist but aerobic soil conditions), 5) actively aerate the soil (regular weed control, enhance nutrient mobilization), and 6) enhance soil organic matter (‘feed the soil, and let the soil feed the plant’) (Kassam and Uphoff 2012). The formulation of principles and practices differs in various sources, with some authors merging some of the above mentioned practices resulting in only four or five practices. Some sources state three to five principles (e.g. Dobermann 2004; SRI-Rice 2012b) from which practices can be derived owing to that fact that SRI is not a standard package of practices (Zhao et al. 2010a). Recommendations can be adapted by farmers to suit the local conditions of their soil, water, fertilizer and manure as well as labor availability. For example, Uphoff (2007) (Uphoff 2007) suggests that compost application is optional.

The SRI methodology aims to provide optimal growth conditions to individual rice plants, thereby maximizing tillering and shortening the phyllochrons “which is believed to accelerate growth rates” (Nemoto et al. 1995, cited in Bouman 2004). The main objective of SRI is to achieve higher factor productivity from land, labor, capital and water used in rice production rather than to maximize rice yields (Uphoff et al. 2002). Initially, de Laulanié developed SRI for irrigated rice cultivation but nowadays its principles are adapted to rice under rainfed conditions as well as to other crops [3].

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[2] If not otherwise mentioned, paragraph 2.1 draws on IRRI (2013), available at http://www.irri.org/index.php?option=com_k2&view=item&layout=item&id=9151&lang=en.

[3] Other crops include wheat, sugar cane, teff, finger millet, maize, pulses, and vegetables. The system can then be referred to as System of Crop Intensification (SCI) (SRI-Rice 2012a).

Many reports show higher yields from SRI fields compared to traditional cultivation methods in many locations, and additional benefits like water saving, reduction in seed required, reduction in mineral fertilizer, resistance to biotic and abiotic stresses, shorter cropping cycle, higher milling outturn, reductions in labor requirements and lower production costs (Kassam and Uphoff 2012).

2.3. Alternate wetting and drying

'Alternately submerged-non-submerged' (SNS) water regime and 'intermittend irrigation' are synonyms for alternate wetting and drying (AWD) (Belder et al. 2005, 2007) (Belder et al. 2005). Under the AWD regime, fields are kept flooded during the first ten days after transplanting (DAT). If many weeds are present in the field, the initially flooded period can be extended to 2 – 3 weeks until the weeds are suppressed. Thereafter, the rice crop is irrigated three to five days after the surface has dried up (Belder et al. 2005). A recommended way to decide on the right moment when to re-irrigate the field is by monitoring the field water depth using a field water tube (for more details, see Bouman & Lampayan 2009). If the water table in the tube drops to 15 cm [4] below the soil surface, the field is irrigated until a water depth of 5 cm above ground. One week before and after flowering, the field should remain flooded. After flowering, during grain filling and ripening, AWD can be practiced again. Just before panicle initiation a non-irrigated period of ten to twelve days is recommended (Belder et al. 2005).

2.4. Aerobic rice systems

Aerobic rice is cultivated just as other upland crops. Special aerobic rice cultivars are grown under aerobic (non-submerged and non-saturated) soil conditions with supplemental irrigation if rainfall is insufficient. Irrigation is usually applied when leaves start to roll. This system is suitable in areas where water is too scarce to allow submerged or intermittently submerged soil conditions.

[4] The threshold of 15 cm is the safe upper limit. Following this safe recommendation, water savings of 15 – 30 % can be achieved. Once confident that AWD does not lead to yield losses, farmers are encouraged to experiment with deeper water levels of 20, 25, 30 cm or deeper in order to increase and optimize water savings, especially when water prices are high or water is very scarce (Bouman and Lampayan 2009).

3 Comparison of different rice cropping systems

The present study tempts an assessment of the rice cropping systems described above in terms of their input use and outputs manifested as yields as well as environmental and socio-economic impacts.

The comparison of different studies on rice cropping systems published in the scientific literature is difficult because of largely different conditions (climatic, soil) and research methodologies (Dobermann 2004). Where appropriate and meaningful, relative data (in percent) was calculated in relation to the reference base for this data, comparable to Bouman and Tuong (2000). However, the agronomic, financial, energy, and environmental costs and benefits are complex and would require systems modeling to develop an understanding of alternative approaches (Keen et al. 2012), which is beyond the scope of this study.

3.1. Water

The amount of water used for irrigation in lowland rice varies according to the type of soil. On heavy clay soils that have a shallow groundwater table (20–50 cm) and that supply water to the crop by capillary raise, the water inputs for crop growth are only 400 mm. Soils with a coarse texture (loamy and sandy) and with deep groundwater tables (1.5 m or more) require more than 2,000 mm for the rice crop (Bouman and Tuong 2001, cited in Bouman et al. 2007, p. 9). Bouman et al. (2007) indicate 1300–1500 mm as the typical average irrigation water input for irrigated rice in Asia. Not all of this water is used by the rice plant. Water flows from the field include evaporation, transpiration, lateral seepage[5] and percolation[6],[7] and possible overbund flows (runoff) (Bouman and Tuong, 2000) (Figure 4). Only transpiration is a 'productive' water flow while all other water flows are nonproductive for the rice crop. Runoff, seepage and percolation account for 25%–50% of all water input in heavy soils with shallow groundwater tables and for 50%–85% in coarsely textured soils with deep groundwater tables (Bouman et al. 2007)

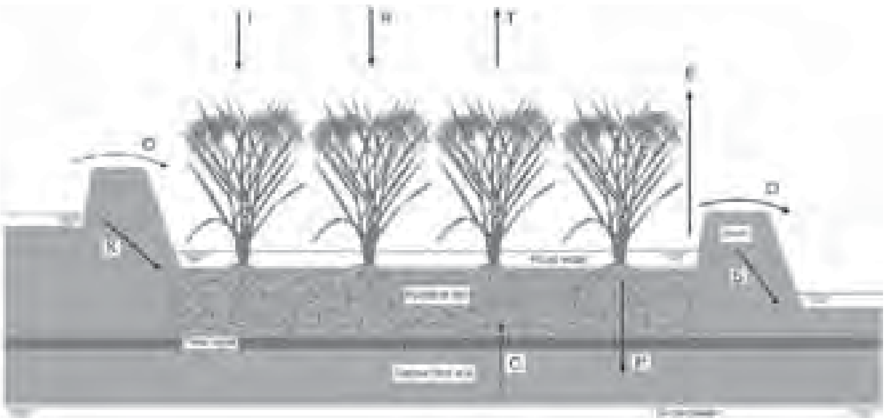


Figure 4 Water balance of irrigated (paddy) rice field

Note:
C, capillary raise; E, evaporation;
I, irrigation; O, overbund flow;
P, percolation, R, rainfall;
S, seepage; T, transpiration

Source: Bouman et al. (2006)

Water productivity can be indicated in different forms: 1) as amount of grain per transpired amount of water, 2) as amount of grain per amount of evapotranspired water or 3) as amount of grain per amount of input water used (Bouman et al. 2007). Water use can be defined as 1) total amount of water from irrigation and rainfall or 2) as evapotranspiration (ET) (Belder et al. 2005). Water use efficiency is usually used synonymously to water productivity.

To estimate water productivity of rice one has to decide at what scale water losses should be taken into account. Water that percolates from the field level to the groundwater or flows to lower lying fields through seepage and overbund flow can be reused further downstream and is hence not really lost. However, 1) percolation, seepage and overbund flow water is lost to the farmer and 2) the recuperation of water further downstream is still linked with costs for some form of energy for pumping. Taking the viewpoint of either field level or larger irrigation system level, water productivity calculations will differ with smaller water productivity at field level and higher water productivity at larger scale level (Table 3). For typical daily water flows from lowland rice, see Table 22 in chapter 7.

Table 3 Water productivity (g rice/kg water) in respect of evapotranspiration (WP_{ET}), irrigation (WP_I) and total water input (WP_{IP}) at different scales

Area (ha)	WP_{ET}	WP_I	WP_{IP}	Location	Source
30–50	0.5–0.6	1–1.5	0.25–0.27	Muda irrigarion system, Kendal, Malaysia	Cabangon et al. (2002)
287–606	1–1.7	0.4–1	–	Zhanghe irrigation system, Hunan, China	Dong Bin et al. (2001)
Over 10^5	–	1–2.5	0.5–1.3		

Source: Tuong and Bouman (2003)

3.1.1. Water use and water productivity

Water savings can be achieved without yield penalties by reducing the losses to nonproductive outflows, in particular to seepage and percolation (Bouman et al. 2007).

Comparing flooding irrigation with non-flooding controlled irrigation (similar to AWD), Xu et al. (2012) find a 57.4% to 63.7% reduction in irrigation water input under the latter, depending on the type of fertilizer regime used (Table 4, compare also chapter 3.4 on fertilizer use).

5 Seepage is the flow of water through bordering bunds.

6 Percolation is the flow of water downwards to soil levels below the root zone.

7 'Typical combined values for seepage and percolation vary from 1–5 mm/day in heavy clay soils to 25–30 mm/day in sandy and sandy loam soils' (Bouman and Tuong, 2001; cited in Bouman et al. 2006 .

Table 4 Water use and percolation losses (in mm) of paddy rice (Japonica variety Jia33) with different water and nitrogen managements (2008)

Irrigation type	Nitrogen management type	IR	ER	WC	ET	PL
Flooding irrigation	Farmers practice (total 403.3 kg N/ha)	878.0 a	346.2 a	1224.2 a	632.0 a	592.2
	Site specific nutrient management (total 162.0 kg N/ha)	855.2 a	368.3 a	1223.5 a	610.6 a	612.9
	Controlled released nitrogen (total 180.0 kg N/ha)	771.2 a	366.3 a	1137.5 a	593.6 a	543.9
Non-flooding controlled irrigation	Farmers practice (total 403.3 kg N/ha)	318.5 b	377.2 a	695.7 b	466.8 b	228.9
	Site specific nutrient management (total 162.0 kg N/ha)	315.0 b	383.3 a	698.3 b	478.6 b	219.7
	Controlled released nitrogen (total 180.0 kg N/ha)	328.2 b	395.3 a	723.5 b	490.1 b	233.4
Change in %	Farmers practice (total 403.3 kg N/ha)	-63.7		-43.2		-61.3
	Site specific nutrient management (total 162.0 kg N/ha)	-63.2		-42.9		-64.2
	Controlled released nitrogen (total 180.0 kg N/ha)	-57.4		-36.4		-57.1

Note: IR: irrigation water, ER: effective rainfall, WC: water consumption, ET: evapotranspiration, PL: Percolation losses.
Within a column, means followed by a different letter are significantly different at 0.05 probability (Tamhane test).

Source: adapted from Xu et al. (2012)

Percolation losses[8] from a non-flooded controlled irrigated paddy field in China were less than half of the losses incurred through percolation in a flooded paddy field. This was confirmed by increased N contents in the top soil until 60 cm of depth after harvest in the non-flooded fields compared to flooded fields (Xu et al. 2012). Water use efficiency (WUE) was significantly larger under non-flooding controlled irrigation compared to flooding irrigation (Table 5). Xu et al. (2012) found a significant interaction effect between nitrogen and irrigation management indicating that fertilization affects water use efficiency differently under different irrigation (Xu et al. 2012).

Table 5 Water use efficiency (WUE, in kg/m³) of paddy rice (Japonica variety Jia33) with different water and nitrogen managements (2008)

Irrigation type	Nitrogen management type	WUEI	WUEET	WUEWC
Flooding irrigation	Farmers practice (total 403.3 kg N/ha)	0.815 a	1.133 a	0.585 a
	Site specific nutrient management (total 162.0 kg N/ha)	0.812 a	1.138 a	0.568 a
	Controlled released nitrogen (total 180.0 kg N/ha)	0.911 b	1.184 a	0.618 a
Non-flooding controlled irrigation	Farmers practice (total 403.3 kg N/ha)	2.185 c	1.491 b	1.000 b
	Site specific nutrient management (total 162.0 kg N/ha)	2.101 c	1.383 c	0.948 b
	Controlled released nitrogen (total 180.0 kg N/ha)	2.053 c	1.375 c	0.932 b

Note: WUEI: water use efficiency with respect to irrigation water, WUEET: water use efficiency with respect to evapotranspiration water, WUEWC: water use efficiency with respect to total water consumed. Within a column, means followed by a different letter are significantly different at 0.05 probability (Tamhane test).

Source: Xu et al. (2012)

Zhao et al. (2010a) report a 57 % reduction in irrigation water use and a 91 % increase in water use efficiency for SRI plots compared to conventional flooded rice.

Table 6 presents water use efficiencies for three upland and four lowland rice varieties under flooded and aerobic cropping conditions.

Krupnik et al. (2012) recorded water savings between 16 % and 48 % in a five season field experiment in the Senegal comparing SRI with the recommended management practices. The least water savings were realized in a rainy season that was relatively rich in rainfall (16 %). Larger savings were realized during the dry seasons (25 % in 2008 and 48 % in 2009).

[8] Percolation losses (PL) were calculated as water consumption (WC) minus evapotranspiration (ET): PL = WC − ET.

Table 6 Water productivity with respect to total water input (WPIR; g grain/kg water) of different varieties grown under flooded and aerobic conditions in the dry season (DS) and wet season (WS) of 2001 – 2003

Rice Type	Variety	Flooded						Aerobic					
		2001		2002		2003		2001		2002		2003	
		DS	WS	DS	WS	DS	WS	DS	WS	DS	WS	DS	WS
Upland	Apo	0.29	0.30	0.58	0.26	0.46	0.41	0.55	0.47	0.67	0.24	0.41	0.36
	IR43	0.34	0.27	0.52	0.17	---	---	0.46	0.44	0.62	0.20	---	---
	UPLRI5	---	---	---	---	0.46	0.35	---	---	---	---	0.39	0.35
Lowland	B6144F	0.22	---	---	---	---	---	0.32	---	---	---	---	---
	IR73868H	---	0.29	---	---	---	---	---	0.46	---	---	---	---
	IR64	---	---	0.56	---	---	---	---	---	0.56	---	---	---
	Magat			0.68	0.32	0.48	0.38	---	---	0.72	0.32	0.49	0.36

Source: Bouman et al. (2005)

This resulted in increased water productivity calculated from the amount of grain harvested per amount of input water used (irrigation water and rainfall) (Table 7). However, the authors point to the risks related to attempts of water saving under farmers' field conditions: Due to difficulties in land leveling, uneven field conditions may occur. This can lead to plant losses where very young seedlings are submerged in parts of the field (Krupnik et al. 2012b) and to higher weed infestation in parts that do not receive sufficient water (Rodenburg and Johnson 2009, cited in Krupnik et al. 2012).

Table 7 Water productivity (kg grain/m^3 water) under recommended management practices (RMP) and the System of Rice Intensification (SRI) for the wet and dry seasons from 2007 to 2009 at Ndiaye, Senegal

Main effect	2007	2008		2009	
	Wet Season	Dry Season	Wet Season	Dry Season	Wet Season
RMP	0.53 b	0.41 b	0.49 b	0.36 b	0.70 b
SRI	0.66 a	0.54 a	0.57 a	0.65 a	0.79 a
F-values	9.20 ***	12.8 ***	5.21 *	17.0 **	5.7 *

Note: Within a column, means followed by a different letter are significantly different according to the LS means t-test with df=1, α= 0.05; * indicates significance at P<0.05, ** indicates significance at P<0.01, *** indicates significance at P<0.001.

Source: Krupnik et al. (2012)

A profitability analysis comparing SRI, best management practices and farmers' practices in Bangladesh in the 2002 – 2003 summer rice season (boro) failed to show a benefit to farmers through reduced water use because the water price was set by the bore whole owner in terms of 'times of watering' and not by actual amount of water used (Latif et al. 2005). The SRI rice took longer time to mature and was therefore irrigated twelve times compared to nine times. The irrigation costs were therefore 33 % higher and reduced the financial benefit that SRI farmers could gain.

The availability of a technical irrigation system and the ability to individually control the flow of water were the two main factors influencing the adoption of SRI at the field plot level in Timor Leste (Noltze et al. 2012). Likewise, the constant and well controlled flow of water input during the whole production phase was stated as a precondition for high-productivity rice production (Gehring et al. 2013). In the reported case of Amazonia, the high evapotranspiration potential together with the shrink-swell behavior of the alluvial soil rendered a periodic drying of the top soil layer unavoidable and resulted in insignificantly but lower grain yields in SRI plots compared to conventionally irrigated plots (Gehring et al. 2013).

3.2 Energy

Rice production ranges among the most energy consuming crops according to Pimentel (2009) (Table 8). However, the author uses an example for rice cultivation with a low yield level from India. When compared with figures from Malaysia, the net energy gain through lowland rice is 8.86 MJ per MJ input, so much higher than the net gain reported from USA by Pimentel.

Table 8 Energy input : output ratio of different crops cultivated in developing countries in comparison to USA

Crop	Country	Yield (t/ha)	Input : output ratio	Input : output ratio of the same crop produced in USA
Maize	India and Indonesia	1.72	1 : 1.08	1 : 4.11
Wheat	Kenya	1.79	1 : 3.31	1 : 2.57
Rice	Valley of Garhwal Himalaya, India	1.83	1: 0.79	1 : 1.42
Rice*	Malaysia	6.47	1 : 8.86	
Rice**	Bangladesh	4.3-4.56	1 : 4.6 – 1 : 6.5	
Rice	USA	7.61	1 : 1.42	
Potato				1 : 2.76
Cassava	Nigeria		1 : 7.57	

Note: *Data from Malaysia from Bockari-Gevao et al. (2005),
** data from Bangladesh from Islam et al. 2011),

Source: if not otherwise mentioned, adapted from Pimentel (2009).

The energy inputs on farms practicing water saving rice cultivation technologies are poorly studied up to date. Ullah (2009, unpublished, cited in Keen et al. 2012) assessed the energy input and outputs of lowland rice on small, medium, and large farms in Central Thailand (Figure 5).

As already mentioned above, in Africa and Asia, rice is grown mainly on small-scale farm holdings that fall into Ullah's small farm category (IRRI 2013). The total energy input per hectare into lowland rice for this farm size was estimated at 14,100 MJ, with tillage energy inputs of 1701 MJ/ha. Main energy inputs originate from fertilizer, seed, followed by harvesting, irrigation and plant protection. A reduction in seed quantity used as realized through SRI would thus consider a considerable reduction in energy input. But also reductions in irrigation water reduce energy consumption as practiced not only in SRI but also by other water saving technologies.

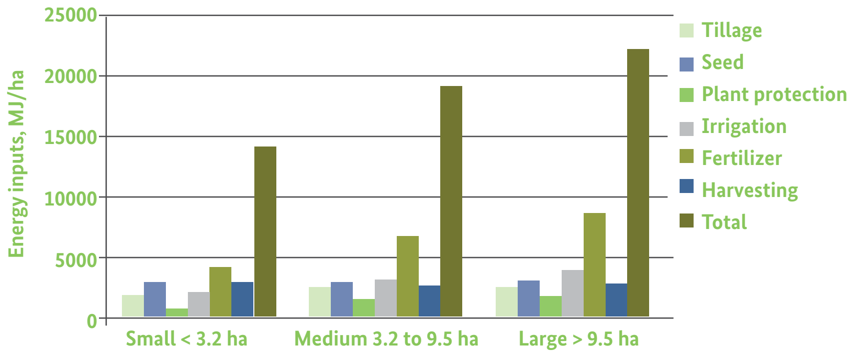


Figure 5 Energy inputs to three size classes of lowland rice farm in Central Thailand.

Source: Ullah (2009), unpublished, cited in Keen et al. (2012)

Table 9 Energy consumption (MJ/ha) based on energy sources under different tillage options

	Conventional tillage and puddling	Puddling & manual forming of beds	58 cm dry bed formed by VMP in a single pass	Dry strip tillage by the VMP in a single pass
Direct energy				
Fuel	2200 (8.2)	2240 (8.5)	1510 (7.5)	540 (2.8)
Human	160 (0.6)	170 (0.6)	250 (1.2)	250 (1.3)
Subtotal	**2350 (8.8)**	**2410 (9.2)**	**1760 (8.7)**	**780 (4.1)**
Indirect energy				
Seed	440 (1.6)	440 (1.7)	440 (2.2)	580 (3.0)
Machinery	4390 (16.4)	3890 (14.8)	1010 (5.0)	600 (3.1)
Fertilizing	9930 (37.1)	9930 (37.8)	9930 (49.0)	9930 (52.0)
Plant protection	3930 (14.7)	3930 (14.9)	3930 (19.4)	3930 (20.6)
Irrigation	5710 (21.3)	5710 (21.7)	3210 (15.8)	3280 (17.2)
Subtotal	**24400 (91.2)**	**23880 (90.8)**	**18510 (91.3)**	**18310 (95.9)**
Total	**26750 a (100)**	**26300 a (100)**	**20270 b (100)**	**19100 c (100)**

Note: Figures in the parenthesis indicate the percentage. VMP: versatile multi-crop planter. In a row, means followed by a common letter(s) are not significantly different at 5 % level by LSD test. LSD0.05 = 0.73, CV (%) = 1.57.

Source: Islam et al. (2011)

Islam et al. (2011) compare energy consumption for rice production under different tillage options including dry seed bed preparation which comes with reduced irrigation (Table 9).

The figures of total energy consumption for different tillage options reveal that dry seed bed preparation that does not include plowing or puddling requires significantly less energy than the wet soil preparation options. This is mainly due to reduced machinery and fuel costs which reduce from 16 % and 15 % of the total energy consumed for conventional tillage and tillage including puddling, respectively to 5 % for dry bed formation and to 3% for dry strip tillage, both using a versatile multi-crop planter. But also the costs for irrigation are reduced from around 21 % (wet soil tillage options) to 16 % and 17 % of the total energy consumption.

Under aerobic soil conditions the energy input into rice cultivation is likely to change due to the possibility to use heavier machines on dry soil compared to moist soil (Keen et al. 2012).

"Electricity and water scarcity can have beneficial effects on increasing the awareness that less water does not harm the rice crop. The problem of water scarcity is intrinsically

linked to the chronically deficient electricity supply. It really depends on the regions" (Zeiske, personal comment 2013).

"Bottlenecks in power supply therefore form a central obstacle for farmers in obtaining irrigation water in time. It is often believed that solving the energy problem will automatically lead to solving the water problem as well. It appears that farmers and some extension officers do not necessarily relate water scarcity to an overexploitation of groundwater resources" (Zeiske, personal comment 2013).

3.3 Labor requirement and gender aspects

It is generally reported that transplanting and weeding is more time consuming under SRI compared with other rice cropping systems (Uphoff and Fernandes 2002; Mishra et al. 2006; Moser and Barrett 2003; Senthilkumar et al. 2008). However, different techniques exist to assist in line transplanting, notably a rope stretched across the field and a simple wooden rake that scores the field surface with lines. The former technique is more time consuming than the rake (Uphoff and Fernandes 2002). The time consumed for seedling preparation and transplanting can be reduced by using seedling trays with individual seed holes (Ceesay et al. 2006). However, Ceesay et al. (2006) do not report the additional investment needed for these seed trays. Table 10 summarizes labor requirements reported in the literature. The figures reveal a large span of time spent for rice cultivation under farmers practice in different countries, reaching from 25 days in Brazil to a total (men and women labor) of 274.5 days in India. Women in the Indian example provided by Senthilkumar et al. (2008) spent more than four times more days in rice cultivation than men.

Table 10 Labor requirements reported in the literature for different rice cropping systems (in ps-d/ha)

Source	Country	Type of work considered	DSP	FP	FAP	BMP/RMP	SRI
Gehring et al. 2013	Brazil	Seedling production and transplanting	1	25			50
Uphoff and Fernandes 2002	Madagascar	Hand weeding					20–25
		Manual push weeder					1 - 5
Noltze et al. 2013	Timor Leste	Total labor		201.75			209.11
Krupnik et al. 2012b	The Senegal	Total labor requirement in 2008		85.2	105.2	103.7	122.2
		Total labor requirement in 2009		95.6	98.7	102.0	148.9
Senthilkumar et al. 2008	India	Labor requirement of men		52			85.5
		Labor requirement of women		222.5			167.5
		Total labor requirement		274.5			253

Note: ps-d: person days; DSP: direct seeding practice, FP: Farmers' practice, FAP: Farmer Adapted Practice, BMP: Best Management Practice, RMP: Recommended Management Practice, SRI: System of Rice Intensification

The changes in required labor comparing different modified rice cropping systems with their reference base do not allow formulating general conclusions. Comparing SRI with famers' practice leads to changes in labor between reductions of about 8 % to increases up to 100 % of time (Table 11). The case presented by Krupnik et al. (2012) further reveals that time requirements for rice cropping are highly season specific: a comparison of SRI with best management practices on labor requirements showed an increase of 18 % in 2008 but an increase of 46 % in 2009.

Table 11 Change in labor requirements reported in the literature for different rice cropping systems (in %)

Based on: Source	Country	Type of work considered	SRI vs. FP	SRI vs. BMP	FAP vs. FP
Gehring et al. 2013	Brazil	Seedling production and transplanting	100		
Noltze et al. 2013	Timor Leste	Total labor	3.6		
Krupnik et al. 2012b	The Senegal	Total labor requirement in 2008	43.4	17.8	23.5
		Total labor requirement in 2009	55.8	46.0	3.2
Senthilkumar et al. 2008	India	Labor requirement of men	64.4		
		Labor requirement of women	-24.7		
		Total labor requirement	-7.8		

Note: ps-d: person days; DSP: direct seeding practice, FP: Farmers' practice, FAP: Farmer Adapted Practice, BMP: Best Management Practice, RMP: Recommended Management Practice, SRI: System of Rice Intensification

Long term measurements of time requirements over several seasons would hence be helpful to produce more reliable mean changes in time requirements. Moreover, long term measurements would provide more reliable information because farmers might become quicker in planting seedlings in modified patterns after several seasons. Barrett et al. (2004) report that time requirements for transplanting and early season weeding was increased during the first three years after adoption but was reduced from the fifth year onwards (Figure 6).

Farmers had to invest more time initially to learn the skills needed for handling young seedlings and planting single seedlings per hill in line or square patterns. Over the same time period, labor productivity was found to initially decline and then to increase from the third to the fifth year.

According to Uphoff and Fernandes (2002), women transplanting SRI seedlings in Sri Lanka felt more comfortable transplanting the lighter and fewer seedlings and reported that it was quicker.

Results from farm survey data from Timor Leste show that labor has the largest production elasticity. This means that a farmer who would invest 1 % more time into rice farming (irrespective of whether she practices SRI or conventional rice farming) would get average yield increases of 0.3 %. So depending on the price of rice and the opportunity costs of labor, it might be beneficial to spend more time for rice cultivation. In Timor Leste, SRI farmers have not adopted compost application and manual weeding yet which could increase time requirements for SRI cultivation. But at the same time, labor requirements for seedling preparation and transplanting might decrease slightly with increasing experience (Noltze et al. 2012).

The most detailed assessment of time requirements was done by Krupnik et al. (2012b) (Table 12).

Farmers in the Senegal experimenting with SRI experienced labor bottlenecks for weeding their SRI crop because higher value vegetable crops required labor for weeding or harvesting at the same time (Krupnik et al. 2012b). However, this was the case only for the dry season because no vegetables are grown in the wet season.

Gender roles in rice cultivation are complex and location specific. Water saving technologies affect men and women differently depending on whether they are paid for their work or not. If female laborers are paid workers, a shift from manual to mechanical weeding would reduce their income from farm work. If they are unpaid workers, it would reduce their drudgery. In the absence of mechanical solutions for weeding, water saving technologies might increase women's work load for weeding, increasing their drudgery or income when unpaid or paid, respectively (Bouman et al. 2007).

Rice farming activities are male dominated in Senegal where women and children are only involved in transplanting and manual weeding (Krupnik et al. 2012b). Looking at labor requirements for weed management in the different rice cropping systems compared in Senegal, Krupnik et al. (2012) found changes in gender dynamics. It seems that the additional mechanical weeding was mostly conducted by men. Additional time requirements for cropping systems like SRI and the farmer adapted management system were hence not at the expense of women.

Likewise, Senthilkumar et al. (2008) report a shift from female labor to male labor in Tamil Nadu, India. Through the modified cropping system (several SRI components were tested), time for rice production in farmers' fields reduced from a total of 274.5 days to 253 days, hence saving 21 labor days overall. While women's labor was reduced by 55 days, due to increased transplanting but decreased weeding time, the labor time of men increased by 33.5 days used for mechanical weeding. However, female laborers are only paid the official labor rate of US$ 0.9 per labor-day which is half the wage for male laborers in India, so that the shift in labor actually increases the costs for agricultural labor from US$ 334 to US$ 342. The actual time reduction was hence not perceived as such by farmers who said they experienced higher labor requirement in 96 % and 20 % of cases in two experimental locations. In the latter location laborers already had experience with line transplanting prior to the on-farm trial. Senthilkumar et al. (2008) report that the female laborers would object to plant in square or line patterns if their employer farmers would ask them to. However, the reasons for this could not be inquired because female laborers could not be interviewed directly in the survey. It could be speculated that the women were also afraid of losing income due to the replacement of their manual weeding time by mechanical weeding. If this was the case, then both farmers and women laborers have an interest in maintaining the conventional rice cropping system in India.

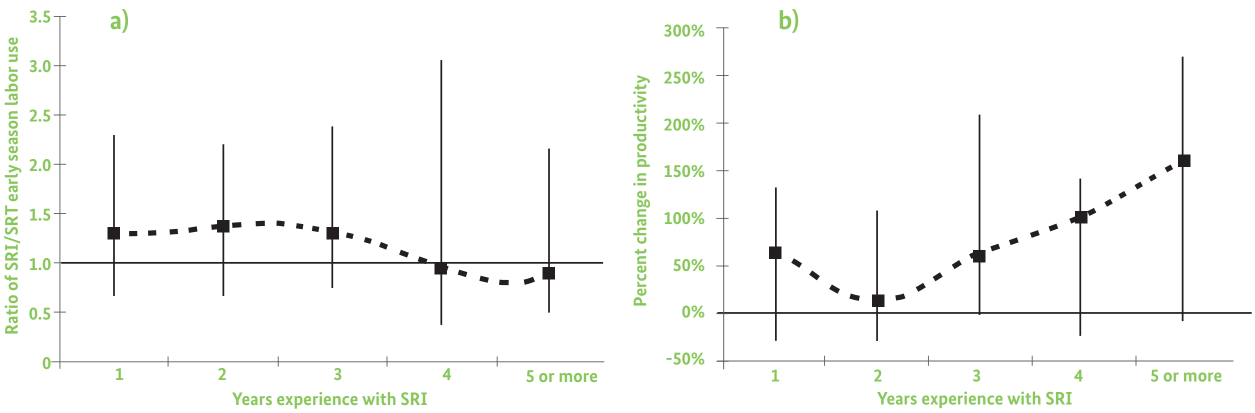


Figure 6 a) Median and span of labor use ratio and b) median and span of the percent change in labor productivity.

Source: Barrett et al. (2004)

Table 12 Labor requirements for different rice cropping systems (in ps-d/ha) in the Senegal

Type of work considered	FP	FAP	BMP/RMP	SRI
Total labor requirement in 2008	85.2	105.2	103.7	122.2
of which...				
Breaking soil clods	20.0	21.7	23.9	14.9
Transplanting	29.7	44.0	38.4	48.1
Herbicide application	2.2	1.3	1.9	0.0
Hand weeding ...	11.3	3.6	15.7	7.4
Mechanical weeding ...	0.0	12.0	0.0	28.6
of which ... weed management by women	11	4	16	
Fertilizer application	1.6	2.4	2.7	2.6
Irrigation/drainage	5.1	4.9	5.8	5.3
Bird scaring	15.3	15.3	15.3	15.3
Total labor requirement in 2009	95.6	98.7	102.0	148.9
of which...				
Breaking soil clods	3.37	4.24	8.02	8.64
Transplanting	54.4	56.4	51.0	77.6
Herbicide application	1.2	1.02	1.07	0.0
Hand weeding ...	18.1	2.0	21.0	1.37
Mechanical weeding ...	0.0	13.8	0.0	38.9
of which ... weed management by women	18	4	21	1
Fertilizer application	1.41	2.29	1.89	2.7
Irrigation/drainage	5.59	7.45	7.53	8.17
Bird scaring	11.5	11.5	11.5	11.5

Note: ps-d: person days; DS: direct seeding, FP: Farmers' practice, FAP: Farmer Adapted Practice, BMP: Best Management Practice, RMP: Recommended Management Practice, SRI: System of Rice Intensification.

Krupnik et al. (2012)

In Amazonia, the extra amount of labor that small scale farmers invest in rice production, allows them to intensify their production in an ecologically sound manner and increase their yield considerably compared to the conventional irrigated agricultural practice for rice. They can hence remain competitive in the absence of scaling effects (Gehring et al. 2013).

Noltze et al. (2012) found no difference in labor input use between SRI adopters and non adopters in Timor Leste.

3.4 Fertilizer

Globally, nitrogen fertilizer applications average 118±40 kg/ha, with the highest levels in southern China (Bouman et al. 2007). Lin et al. (2007, cited in Xu et al. 2012) report application rates in the Tai-lake area in China of averaging 300 kg N/ha with some farmers applying up to 350 kg N/ha of chemical N fertilizer.

However, irrigated lowland rice utilizes not all of the applied N fertilizer and considerable amounts of N are lost through leaching, denitrification, and ammonia (NH_3) volatilization leading to water, soil and atmospheric pollution (Zhao et al. 2010a). In China, nitrogen use efficiency is only about 30-35 %; up to > 50 % of fertilizer N is lost according to Qin, Fan and Wang (2001, in Chinese, cited in Zhao et al. 2010a).

Gehring et al. (2013) examined the effects of low-input vs. high-input regimes of fertilizers. The low-input regime consisted of 10 t/ha of cow manure and the high-input regime of 10 t/ha of cow manure plus 100 kg N/ha as urea. The bi-factorial ANOVA revealed that the main effect of fertilizer application was significant. Root and shoot biomass, plant height, and grain yield increased in both compared cropping systems (SRI and conventional irrigated) due to the additional urea application (Gehring et al. 2013).

Krupnik et al. (2012a) (Krupnik et al. 2012a) showed that farmers in the Senegal would benefit from SRI over the long term when applying a combination of organic matter (e.g. rice straw) and mineral fertilizers. The sub-treatment that combined straw with mineral fertilizer applications had a better effect on macronutrient uptake under SRI than under the recommended Senegalese management practice. The positive effects of straw application appeared only from the fourth cropping season onwards. This might be due to a slow build up of a pool of soil nutrients. Krupnik et al. (2012a) conclude that resource-poor farmers who cannot afford a balanced N-P-K fertilizer would benefit from the combined organic matter plus mineral fertilizer regime, although positive effects might only appear over time.

Krupnik et al. (2012a) observed improved recovery of N from straw and fertilizer that contributed to additive yield effects under SRI in the last two cropping seasons of their experiment. In the fifth and final season, the N recovery from straw under SRI was higher than 100 % suggesting that N was provided by the labile N pool of the soil which was most likely built up through repeated straw applications during the previous cropping seasons. Integrated organic and mineral fertilizer applications had a positive effect on soil quality parameters and on partial macronutrient balances. However, recovery of fertilizer N was not significantly increased under SRI (Krupnik et al. 2012a).

Farmers in the Senegal explained that they preferred to apply the limited organic matter available to higher value crops like vegetables (Krupnik et al. 2012b).

Since fertilizer treatments have direct impacts on yields more details on fertilizer effects under different cropping systems can be found in chapter 3.7 on grain yields.

3.5 Weed occurrence and pesticide use

The type of rice crop management practices (type of crop establishment, water management, mechanical and chemical weed control management) and their interactions affect the weed occurrence and species composition in rice fields (Bhagat et al. 1996). Influences and interactions are complex and are further complicated by site specificity. In general, a high water level in flooded rice fields is an effective means for controlling weed species. Under flooded conditions, only amphibious or aquatic weeds can survive. However, weed species respond differently to changing water management. Under flooded conditions, C-3 weeds dominated over C-4 weeds while in saturated soils and under upland conditions, C-4 weeds accounted for 90 % of the dry mass compared to only 10 % under flooded conditions (Tanaka 1976, cited in Bhagat et al. 1996).

Senegalese farmers who participated in a farmer-researcher collaborative field experiment, considered the use of pesticides at high rates used in a recommended management practice treatment as too costly to adopt it under their circumstances. The recommended dose was 8 l/ha of Propanil and 1 l/ha of 2,4-D compared to 5.2 and 0.8 l/ha of the two pesticides, respectively under farmers' practice. Reasons they put forward were poorly functioning credit systems and value chains that hampered the timely and consistent availability of large amounts of herbicides (Krupnik et al. 2012b). The farmer adapted management practice that was jointly developed and tested resulted in 40 % and 11 % reduction in herbicide use compared to recommended practices and farmers practices in 2008 and in a 52 % and 34 % reduction, respectively, in 2009.

In 2008, the best weed control was achieved with recommended management practice (high levels of pesticide) and farmers adapted practice (combination of weeding and herbicide application) at booting stage (Krupnik et al. 2012b). In 2009, only fields that were operated following farmers' practice had significantly more weed biomass while all other management practices (SRI, RMP, and FAP) had similar amounts of weed biomass.

Results from farm survey data from Timor Leste show that yield is affected significantly by pesticide applications under SRI while it is not affected under conventional rice management (Noltze et al. 2013). Mechanical weed control is not always adopted with SRI in Timor Leste although weeds occur more abundantly under non-flooded conditions and hence farmers might rely more often on herbicides under SRI.

3.6 Farmers' perceptions, problems and risk adaptation practices

Farmers in the Senegal perceived very young seedlings as less adapted to agronomic stresses and preferred older seedlings for transplanting (Krupnik et al. 2012b). Some of them had experienced seedling mortality under SRI and had to fill the gaps after transplanting. Although linked with higher labor requirements, farmers perceived line planting as advantageous for weeding and crop development.

In an irrigation system where water was pumped following a pre-defined weekly schedule, farmers offset the risk of pump failures by irrigating large amounts of water into their field. The deep water served as buffer and thus reduced their drought risk. They were reluctant to adopt an alternate wetting and drying practice. In another irrigation scheme, where water was available to individual farmers every 3 to 5 days, farmers found it easy to adopt AWD. In the irrigation scheme where farmers managed the water flow on their own it was easy to adapt irrigation frequency and amounts to SRI requirements (Krupnik et al. 2012b). However, overall, farmers used alternate wetting and drying practices mainly in the later vegetative growth stages because they felt that higher water levels at early stages were necessary for weed control.

Farmers perceived that difficulties of even land leveling, difficulties in water control and management, and shortages in labor availability were the three top most constraints to realizing larger water savings. The difficulties related to pumping frequency were already mentioned above. In commonly used water canals, free riding might occur when only a few farmers make efforts to save water. Reliable methods to measure water inflow at the field level would be required to equitably distribute irrigation fees among water users. However, as long as such methods are not available, Krupik et al. (2012) suggest that farmers would need to adopt improved governance procedures to implement water savings at the irrigation scheme level.

Farmers in Tamil Nadu have no incentive to save water because both irrigation water and electricity for pumping are free of charge for farmers. Some experienced difficulties in adopting water saving irrigation because their fields were located in a cascade system of irrigation (Senthilkumar et al. 2008). The three top most reasons for farmers to be interested in SRI were (1) increases in yield and profit, (2) reduction in costs, and (3) low initial capital investments. Ecosystem conservation, long-term sustainability and water savings were among the least important reasons (Senthilkumar et al. 2008).

About 40 % of farmers using a mechanical cono-weeder in heavy clay soil in Tamil Nadu complained about the heavy weight and difficulty of handling the tool (Senthilkumar et al. 2008).

3.7 Grain yields

Grain production did not differ (although lower, but insignificantly) comparing SRI production with conventional irrigated production system in a field trial in the eastern periphery of Amazonia, Brazil (Gehring et al. 2013). Still, the bi-factorial ANOVA showed significant main effects of the production systems as well as of the fertilizer regime.

Krupnik et al. (2012a) examined yield effects of SRI and management practices recommended in the Senegal in a field experiment conducted over five cropping seasons between 2007 and 2009. During the three first experimental seasons, there was no significant effect of the cropping system on the grain yield. The only significant yield effect occurred in response to fertilizer application in seasons one to three (Krupnik et al. 2012a).

Table 13 **Grain yield from different rice cropping systems under two fertilizer regimes in Amazonia**

Production system	Grain yield in t/ha	
	Low fertilizer input: 10 t/ha of cow manure	High fertilizer input: 10 t/ha of cow manure + additional 100 kg N/ha
System of Rice Intensification	3.2a	5.7b
Conventional irrigated rice	4.4a	6.2b
Change in %	-27.3 %	-8.0 %

Note: different letters indicate significant differences between treatments (Tuckey p<0.05).

Source: Gehring et al. (2013).

In the fourth experimental season (2009 dry season), the application of fertilizer and fertilizer plus straw affected yields under SRI more positively than under the recommended management practice (significant fertilizer x management system interaction, $P < 0.05$). Both, fertilizer and straw application had significant and positive yield effects. Their interaction term remained insignificant, suggesting that their effects are additive under both management systems. However, their positive effect only occurred four seasons after the start of straw incorporation (Krupnik et al. 2012a).

In the fifth season, yields under the recommended management practice followed a similar pattern than observed during the first three seasons, responding only to mineral fertilizer application. In contrast, yields under SRI increased with increasing nitrogen application originating from both fertilizer and straw. When averaged across all sub treatments, SRI yielded slightly but significantly less than the recommended management practice in the fifth season. In the previous seasons, the systems did not differ significantly in yield. So, SRI yields were lower in only two of 20 observed experimental cases. But overall, no sustained yield advantages of SRI over the recommended management practices were found (Krupnik et al. 2012a).

In a farmer participatory experiment in the Senegal, both, SRI and recommended management practices significantly outperformed farmers' practice without any significant difference between the two afore mentioned management systems in terms of grain yield (Krupnik et al. 2012b).

Zhao et al. (2010a) examined yield effects comparing SRI with traditional flooding (TF) under different N application rates in China and found a 22 % of yield increase averaged over all N levels. Differences in yield were significant at 0 and 80 kg/ha of N applied and highest at 80 kg/ha of N applied. At higher N levels (160 and 240 kg N/ha) the yield was still higher though not significantly under SRI compared to TF.

Simple comparison of rice yields did not show significant difference between SRI adopters and non-adopters (Noltze et al. 2012). Noltze et al. (2012) suggest several possible reasons for the lower than expected yield: (1) farmers adopted SRI techniques on plots with lower than average yield potential (negative selection bias), (2) SRI might not be a suitable technology for the general cropping conditions in Timor Leste, (3) adopting farmers might have limited experience and lack the capacity to fully exploit the potential of SRI, and (4) farmers who adopted SRI were more likely to also have adopted rice seed distributed by the local extension service that was of lower quality and had poor germination properties. When controlling for selection bias (SRI was found to be adopted more in conditions with less than average yields), the authors find significant gains in yield. This means that adopters would have significantly lower yields if they had not adopted SRI (ATT: 45.7 %). If non adopters would adopt SRI under their field conditions, yield gains could be around 11 % (Noltze et al. 2013).

Anitha and Chellappan (2011) did not find any difference in rice yield (grain yield, straw yield, net return and other yield parameters) comparing continuous and intermittent irrigation in Kerala suggesting that a reduction in water input does not affect the yield. They found however increased weed occurrence in the intermittently irrigated area.

Different rice varieties have different yield potential under different cropping environments. Examples of yields achieved by different rice varieties are given in Table 14, Table 15, and Table 23 comparing upland and lowland cultivars under flooded and aerobic cropping conditions[9], comparing a Japonica rice variety under flooded and SRI cropping conditions as well as presenting 38 Indian indigenous rice varieties cultivated under SRI in different agro-ecological conditions.

Possible reasons for yield advantages under SRI (when observed) put forward in the literature are higher microbial activity (Zhao et al. 2010a), the 'Birch effect' (increased N availability when re-wetting dry soil) (Birch 1958), and increased root mass and root activity (Xu et al. 2003; Lu et al. 2006, both in Chinese, cited in Zhao et al. 2010).

Table 14 Grain yield (t/ha) of different varieties grown under flooded and aerobic conditions in the dry season (DS) and wet season (WS) of 2001 – 2003

Rice Type	Variety	Flooded						Aerobic					
		2001		2002		2003		2001		2002		2003	
		DS	WS	DS	WS	DS	WS	DS	WS	DS	WS	DS	WS
Upland	Apo	5.06 b	5.31 a	7.33 b	4.99 b	6.80 a	5.99 a	4.36 a	4.19 a	5.66 ab	3.49 b	4.00 b	4.20 a
	IR43	5.90 a	4.77 b	6.59 c	3.12 c	---	---	3.56 b	4.10 a	5.19 bc	2.92 c	---	---
	UPLRI5	---	---	---	---	6.87 a	5.30 b	---	---	---	---	3.82 b	4.03 a
Lowland	B6144F	3.85 c	---	---	---	---	---	2.55 c	---	---	---	---	---
	IR73868H	---	5.21 a	---	---	---	---	---	4.19 a	---	---	---	---
	IR64	---	---	7.08 b	---	---	---	---	---	4.68 c	---	---	---
	Magat	---	---	8.66 a	6.02 a	7.19 a	5.56 b	---	---	6.03 a	4.61 a	4.80 a	4.20 a
LSD (0.05)		0.58	0.30	0.62	0.38	0.75	0.27	0.29	0.50	0.56	0.51	0.48	0.40

Note: Within a column, means followed by a different letter are significantly different at 0.05 probability level according to least significant difference (LSD) test.

Source: Bouman et al. (2005)

Table 15 Grain yield (t/ha) of the Japonica variety Bing 98110 grown under traditional flooded rice cultivation and SRI in Zhejiang Province, China in 2004

Variety	Traditional flooded rice cultivation	SRI	Change in %
Japonica (Bing 98110)	7.94	6.28	-20.9

Source: Zhao et al. (2010a)

3.8 Production economics and impact on poverty

In both 2008 and 2009 dry and wet season, farmers achieved the highest profits with the highest rate of return from the adapted management practice they had jointly developed with researchers in the Senegal and which blended SRI with recommended management practices (Table 16) (Krupnik et al. 2012b). Although production costs increased by 15 % (RMP) and 9 % (SRI and FAP) in 2008 and by 22 % (RMP) and 9 % (SRI and FAP) in 2009 over farmers' practice, the yields obtained from improved management practices were all significantly higher compared to farmers' practice.

Profitability calculations might change in favor of SRI if the savings from reduced irrigation water could be taken into account. However, it was not possible in farmers' field experiments to measure the irrigation water inflow for different cropping systems. Therefore, Krupnik et al. (2012b) estimated the potential impact of water savings on net profit comparing SRI with recommended management practices. Assuming no yield loss, the authors calculated that the net profits of SRI would break even with those of recommended management practices in 2008 if a minimum of 50 % and 36 % of water savings were realized in Guia-4 and Oumar Youness, respectively. Water savings of 41 %-42 % would be required for SRI to break even in 2009. Although water savings of more than 50 % have been reported for Asia, water savings measured in the Senegal ranged between 16% and 48 %, depending on the season (Krupnik et al. 2012a). In this context it has to be considered that irrigation water measurements are usually taken under experimental station conditions with small field plots where the control of water is relatively easy. Under farmers' conditions, it might therefore be more difficult to achieve comparably high water savings (Krupnik et al. 2012b).

Krupnik et al. (2012b) constructed descending cumulative distribution functions (CDFs) to examine the probability of achieving minimum profit levels through the use of alternative management systems (Figure 7). The cumulative distribution functions describe the probability of achieving a certain profit. For instance, following farmers practices would result in a minimal profit of 360 €/ha at a probability of 56 %. Hence there would be a 44 % risk of achieving a lower profit. The CDFs in Figure 7 show that all improved management systems have curves shifted to the right, hence reduce farmers' risks considerably and increase their success rates by shifting the potentially achievable profits to higher levels.

9 The calculated changes in yields (in %) comparing aerobic with flooded rice are shown in Table 24, chapter 7.

Table 16 **Profitability analysis of rice management systems during 2008 wet and 2009 dry seasons at three sites in the Senegal**

Year		Location	FP	FAP	BMP/RMP	SRI
2008	Total production costs (€/ha)	Nianga	423	483	482	506
		Guia-4	407	442	441	494
		Oumar Youness	571	616	623	654
	Yield (t grain/ha)	Nianga	3.79	5.36	4.91	5.10
	(unit price: 0.21 €)	Guia-4	4.19	5.07	4.79	4.79
		Oumar Youness	4.08	5.84	5.28	5.11
	Profit (€/ha)	Nianga	375	644	551	566
		Guia-4	475	624	568	515
		Oumar Youness	287	614	487	420
	Rate of return	Nianga	0.89	1.33	1.14	1.12
		Guia-4	1.17	1.41	1.29	1.04
		Oumar Youness	0.50	1.00	0.78	0.64
2009	Total production costs (€/ha)	Nianga	556	533	574	630
		Guia-4	435	545	548	627
		Oumar Youness	-	-	-	-
	Yield (t grain/ha)	Nianga	4.32	6.06	5.84	6.05
	(unit price: 0.18 €)	Guia-4	3.98	7.51	7.44	7.42
		Oumar Youness	-	-	-	-
	Profit (€/ha)	Nianga	228	560	520	450
		Guia-4	287	817	802	720
		Oumar Youness	-	-	-	-
	Rate of return	Nianga	0.41	1.04	0.96	0.69
		Guia-4	0.66	1.50	1.46	1.15
		Oumar Youness	-	-	-	-

Note: FP: Farmers' practice, FAP: Farmer Adapted Practice, BMP: Best Management Practice, RMP: Recommended Management Practice, SRI: System of Rice Intensification; Rate of return = profit/production costs, profit may differ slightly from the difference in production value and costs because of rounding; Because of crop loss from severe granivorous bird attack in Oumar Youness, 2009 dry season data are not shown.

Source: Krupnik et al. (2012b)

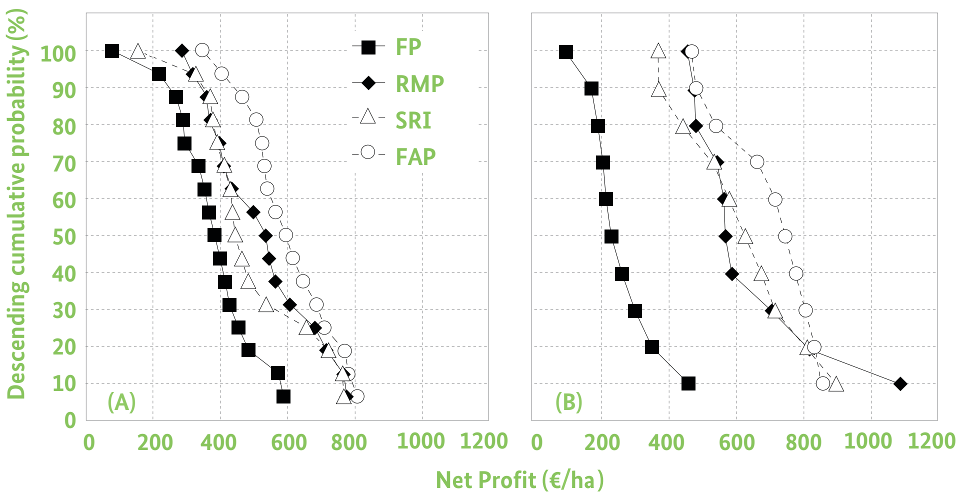


Figure 7 **Descending cumulative distribution functions in the 2008 wet season (A) and the 2009 dry season (B)**

Note: Descending cumulative distribution functions describing the potential (y-axis) of obtaining profits (€/ha) greater than values on the x-axis for all farmers from Farmers' Practices (FPs), the System of Rice Intensification (SRI), Recommended Management Practices (RMPs) and Farmer Adapted Practice (FAP).

Source: Krupnik et al. (2012b)

Similarly as in the case of yield, a simple comparison of household income in Timor Leste does not show significant difference between SRI adopters and non-adopters (Noltze et al. 2012) (Table 17). However, total variable costs are significantly lower under SRI, largely due to lower seed costs and lower pesticide costs. Fertilizer costs (chemical fertilizer in this case) are only slightly but still significantly higher for SRI while no significant difference was found in labor inputs.

Although a simple comparison of income did not reveal a significant difference between adopters and non-adopters, when controlling for selection bias[10], the authors find significant but small gains in incomes. The average effect of SRI adoption on adopters (the average treatment effect on treated: ATT) is 2.3 % in terms of household income. The relatively small change is explained with diversified incomes of SRI farmers for which rice production accounts for 32 % of income compared with 39 % of income from rice for non SRI adopters. Also, household heads whose main activity is farming are less likely to adopt SRI, probably due to the fact that they lack external contacts and thus participate less in information exchange compared to farmers who have more off-farm activities.

The ATU (average treatment effect on untreated) of -2.2 % suggests that non adopters would not gain economically from adopting SRI which justifies their decision. This also shows that the impacts of SRI adoption are very context specific and depend on micro-level socioeconomic and agro-ecological conditions (Noltze et al. 2012).

Table 17 **Costs and returns on SRI and conventional rice plots**

	All	(SD)	SRI	(SD)	Conv.	(SD)	Diff.	
Yield (tons/ha)	3.13	(2.53)	2.94	(2.22)	3.24	(2.69)	0.30	
Market price for paddy rice (US$/ha)	0.30							
Gross revenue (US$/ha)	898.38	(767.75)	865.70	(670.08)	916.10	(816.34)	-50.40	
Seed quantity (kg/ha)	51.80	(68.66)	14.47	(19.98)	72.38	(76.86)	-57.90	***
Seed costs (US$/ha)	20.72	(27.46)	5.79	(7.99)	28.95	(30.74)	-23.16	***
Pesticide and herbicide costs (US$/ha)	15.99	(17.83)	14.09	(15.21)	17.03	(19.05)	-2.93	*
Fertilizer costs (US$/ha)	8.58	(22.57)	12.33	(27.40)	6.52	(19.16)	5.81	***
Labor (days/ha)	204.35	(149.76)	209.11	(151.58)	201.75	(148.94)	7.36	
Hired labor costs (US$/ha)	125.87	(129.71)	115.84	(126.62)	131.36	(131.24)	-15.53	
Total variable costs (US$/ha)	171.25	(142.59)	148.06	(139.16)	184.03	(143.08)	-35.96	***
Net income (US$/ha)	725.91	(756.22)	717.64	(645.26)	730.39	(811.02)	-12.74	

Note: *, **, *** Statistically significant at the 10 %, 5 % and 1 % level, respectively.

Source: Noltze et al. (2013)

It has to be considered that most costs are encountered by the individual farmers while some of the benefits, namely reduced water use and environmental conservation accrue at the society level (Noltze et al. 2012).

Latif et al. (2005) conducted a profitability analysis in an experimental design comparing SRI, local best management practices (BMP) and farmer's practices. Due to high labor costs for weeding and the specific local price setting scheme for irrigation water, the SRI production was equally profitable to the farmers' practice and both were inferior compared to the BMP. The irrigation water price in the experimental area in Comilla district (Bangladesh) was decided by the tube well owner in terms of the times of irrigation and not according to the actual amount of water that was used. Under such water pricing conditions, farmers fail to materialize the benefits from reduced water use through SRI.

Noltze, Schwarze, & Qaim (2012) examine the impact of SRI adoption on poverty and reveal that the technology has a poverty alleviating potential: both poor[11] and non-poor farmers benefit from adopting SRI. Poor farmers realize an income gain of 2.1 % by adopting SRI. The authors also show that small-scale farmers with less than 2 ha of land have an income gain of 4.8 % which is significantly higher than the gain realized by farmers cultivating larger farms.

3.9 Environmental impacts

Increased mineral fertilizer and chemical pesticide use have led to environmental pollution worldwide. High dosages of fertilizer that cannot be absorbed by the plants are lost to the soil, water and atmosphere leading to eutrophication, acidification and changes in biodiversity. Leaching of nitrogen from rice fields accounts for 30 % – 50 % of N losses, 10 % – 30 % are lost through denitrification (Ghosh and Bhat 1998), up to 30 % are lost through ammonia volatilization when fertilizer is incorporated into the soil and up to 50 % are lost when fertilizer is applied as top dressing (Hayashi et al. 2008).

3.9.1 Ammonia volatilization

Ammonia (NH_3) volatilization is the major fraction of N loss in irrigated rice production accounting for 0.41 % to 40 % of the applied N in China (Gao et al. 2002, cited in Zhao et al. 2010). Xu et al. (2012) reviewed the literature on ammonia volatilization from paddy fields. They summarize that losses range between 10 % and 60 % of applied N fertilizer and give examples of various factors influencing ammonia volatilization (Xu et al. 2012) (Table 18).

[10] The calculated changes in yields (in %) comparing aerobic with flooded rice are shown in Table 24, chapter 7.
[11] Defined by Noltze et al. (2012) as farmers earning less than US$ 0.94 a day.

Table 18 Factors influencing ammonia volatilization

Factor	Higher ammonia volatilization	Lower ammonia volatilization	Source
Climatic condition			
Temperature, Wind, Sunshine hours	Higher temperature, wind speed and sunshine hours	Rainy and cloudy weather	Freney et al. 1981; Denmead et al. 1982
Nitrogen fertilizer application			
Fertilizer type	Ammonium bicarbonate	Urea	Cai et al. 1986; Zhu et al. 1989
Application method	Top dressing of N	Puddling of N fertilizer into plowed soil layer	Fillery et al. 1984; Cai et al. 1986; Obcemea et al. 1988; Zhu et al. 1989; Hayashi et al. 2008
Fertilizer amount	Large amounts		Xu et al. 2012; Zhao et al. 2010; Li et al. 2008
Field water management			
	System of Rice Intensification		Zhao et al. 2010
		High flood water level	Freney et al. 1988; Williams et al. 1990
		Zero-drainage management during first flooding-drying cycle after N application	Li et al. 2008
	Moist soil	Muddy soil	Scivittaro et al. 2010

Source: adapted from Xu et al. (2012)

The volatilization of ammonia depends on climatic conditions, the method of nitrogen fertilizer application, and field water management (Bouman et al. 2007). Volatilization losses in a Chinese experiment were increased by 23.6 % to 46.7 % through SRI cultivation compared to traditional flooding (Zhao et al. 2010a).

However, the losses were low compared to the maximum losses reported from China (Gao et al. 2002) and India (Ghosh and Bhat 1998) and were ranging only between 3 % and 6 % of the total N applied. Not surprisingly, volatilization losses increased with increasing fertilizer N applications in both, SRI and TF treatments.

Looking at ammonia volatilization under different water management and N application conditions revealed that N application is the more dominant factor of both (Xu et al. 2012) (Figure 8).

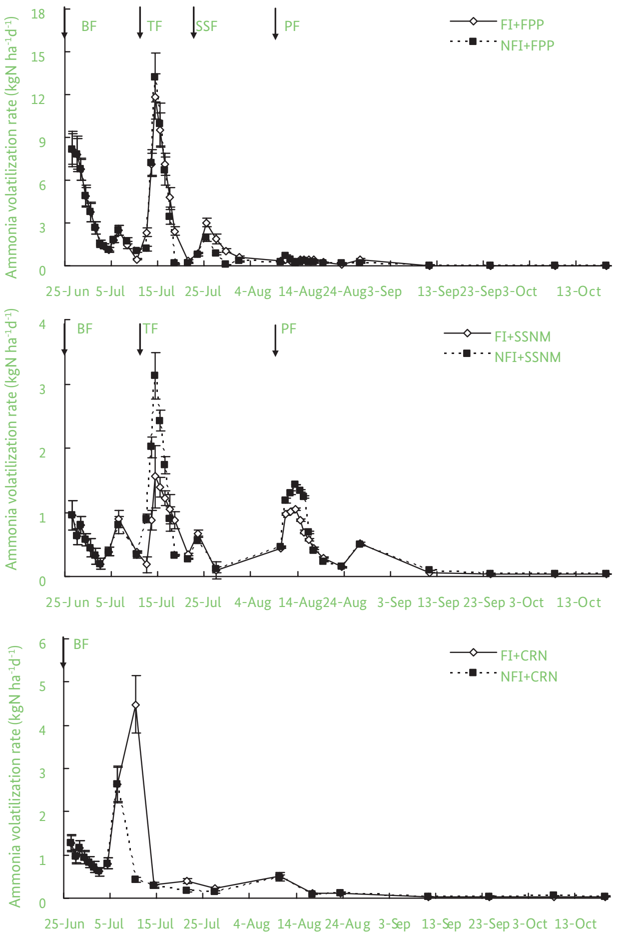


Figure 8 Ammonia volatilization rates from rice paddy with different water and N managements

Note: FI and NFI are flooding irrigation and non-flooding controlled irrigation. FFP, SSNM and CRN are farmers' fertilization practice, site specific nutrient management and controlled released nitrogen management. BF, TF, SSF and PF are basal fertilizer, tillering fertilizer, fertilizer for strong seedling and panicle fertilizer.

Source: Xu et al. (2012)

Ammonia volatilization losses followed similar patterns comparing different irrigation practices but showed distinct patterns when looking at different N application types.

Losses were highest for farmers' fertilization practices (total of 403.3 kg N/ha applied to field) and lower for site specific nutrient management and controlled released nitrogen management (Table 19).

Table 19 Seasonal ammonia volatilization losses from rice paddy with different water and nitrogen management, Tai-lake region, China (2008)

Treatment	Amount (kg N/ha)	Share of seasonal inputs (%)	Reduction of seasonal losses compared to FI+FFP (kg N/ha)
FI + FFP	145.64 a	36.1	-
FI + SSNM	32.11 b	19.8	113.53
FI + CRN	33.30 b	18.5	112.34
NFI + FFP	125.27 a	31.1	20.37
NFI + SSNM	37.63 b	23.2	108.01
NFI + CRN	23.73 b	13.2	121.91

Note: Descending cumulative distributiNote: FI and NFI are flooding irrigation and non-flooding controlled irrigation. FFP, SSNM and CRN are farmers' fertilization practice, site specific nutrient management and controlled released nitrogen management. BF, TF, SSF and PF are basal fertilizer, tillering fertilizer, fertilizer for strong seedling and panicle fertilizer.

Source: Xu et al. (2012)

Following farmers' fertilization practices, 36 % and 31 % of applied nitrogen are lost from flooded and non-flooded fields, respectively. Peaks of ammonia volatilization occurred shortly after fertilizer applications, with particularly high peaks after the first two applications of the cropping season (basal fertilizer applied shortly before transplanting and tillering fertilizer applied 15 DAT). Losses occurring within one week after these two application dates constitute the majority of seasonal ammonia volatilization losses due to high fertilizer dosage and non established canopy cover. Due to the fact that water depths in non-flooding controlled irrigation were kept shallower than in the flooded irrigation treatment, volatilization losses were higher in the non-flooded controlled irrigation fields. But as soon as the water cover disappeared in the non-flooded controlled irrigation field, losses reduced to below the volatilization losses occurring in the flooded field confirming results of Hayashi et al. (2006, cited in Xu et al. 2012). Volatilization losses from site specific nutrient management fields were similar but much lower than losses from the farmers' fertilizer practice field. In contrast, the losses from controlled released nitrogen management field followed a different pattern. Losses from the flooded field were higher than those from the non-flooded field and occurred four days later. Lowest losses were measured from the non-flooded controlled irrigation field with controlled released nitrogen management (23.73 kg N/ha accounting for 13.2 % of seasonally applied N) (Xu et al. 2012).

While ammonia volatilization was lower under high flood water levels compared to lower water levels, the water depth had no significant influence on total nitrogen lost from the rice field (Freney et al. 1988). The soil conditions under the experiment conducted by Freney et al. (1988) had high nitrification and denitrification rates. Therefore, the authors conclude that under similar soil conditions, water depth cannot be used to increase the N fertilizer use efficiency of rice plants. In soils that show high ammonia volatilization but have lesser N losses through nitrification fertilizer use might be improved through increased water levels.

3.9.2 Soil fertility

Zhao et al. (2010b) report increased soil microbial biomass under SRI conditions compared to traditional flooded rice. However, it is not clear whether this increase was due to the application of organic fertilizer (1125 kg/ha of rape seed cake containing approximately 4.6 % N) or to increased root mass and activity that might stimulate the proliferation of microorganisms (Zhao et al. 2010b) . The authors conclude that their results provide evidence that SRI could improve soil fertility.

Soil structure was shown to be affected by repeated wetting and drying cycles. In a micromorphological analysis to characterize structure modifications of soil samples submitted to wetting and drying cycles Pires et al. (2008) found that pore volume increased for all three soils tested (Geric Ferralsol, Eutric Nitosol, and Rhodic Ferralsol) after repeated wetting and drying processes.

When measured after five cropping seasons with fertilizer and straw[11] incorporations under SRI and recommended management practices in the Senegal, Krupnik et al. (2012a) found that straw application increased total soil C and N significantly and thus improved soil quality under both management systems.

[11] In SRI the use of considerable amounts of organic matter like compost is recommended. Straw was applied instead of the compost because compost production in the Sahel is difficult due to limited availability of biomass and labor.

4 Under what conditions is the adoption of water saving technologies beneficial?

4.1 General considerations

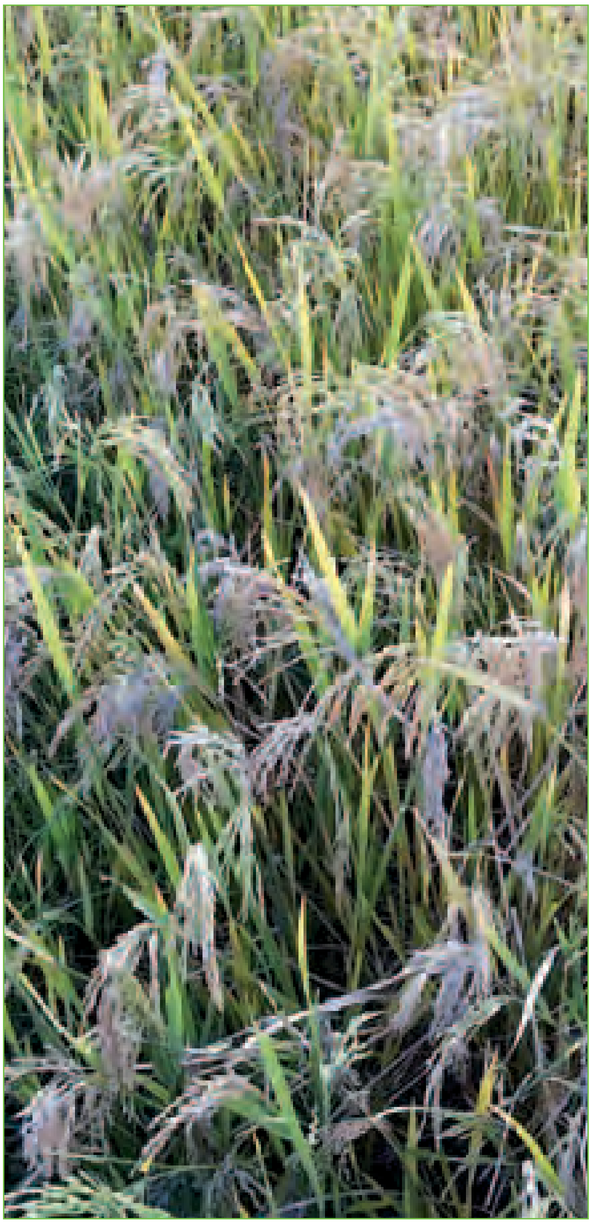
The location related to the farmer's homestead and accessibility of the rice plot is important for the success of rice cultivation under SRI. Noltze et al. (2013) found that the time required to reach the rice plot has no effect on yield in conventional rice cropping while it has a significant effect on yields under SRI. With increasing distance from the homestead, yields reduce in Timor Leste. The authors also found that farmers with smaller farm sizes benefit from SRI adoption over-proportionally compared to bigger farms.

4.2 Soil conditions

Soils where SRI was first tested in Madagascar are mostly Oxisols, Ultisols, Entisols, and Inceptisols (IRRI 1997, Soil Survey Staff 1999, both cited in Dobermann 2004). About 60 % of all soils in Madagascar have ferralitic properties and low soil fertility (Oldeman 1990, cited in Doberman). The major soil characteristics of these soils are low CEC, low exchangeable cations, acid pH, large amounts of Fe- and Al-oxides, predominantly 1:1 layer clay minerals, and a high potential for accumulation of soluble ferrous iron and manganese after flooding which are toxic for rice plants under submerged conditions (Dobermann

2004). Under continuous flooding regimes on such soils, the yields of rice tend to be very low due to negative effects on rice growth during the vegetative phase brought about by the unfavorable physico-chemical soil characteristics (Vizier et al. 1990, cited in Dobermann 2004). SRI and other rice cropping regimes with more aerobic soil conditions can have potential for yield increase on these soils. However, Doberman (2004) highlights the fact that most soils under continuous flooding regimes in Asia are mostly of higher fertility status (typically Entisols, Inceptisols, Alfisols, Vertisols, and Mollisols). Vast areas of Ultisols exist but are mostly used for rainfed lowland and upland rice and larger areas of Aquults exist in Indonesia, India, the southern Philippines, and Sri Lanka but their relative share in irrigated rice production is small (Dobermann 2004).

Gehring et al. (2013) state that the shrink-swell property of the alluvial soils in eastern Amazonia temporally disrupted the water flow paths from the soil to plants and possibly also damaged finer roots, resulting in lower grain yield. Keeping a constant soil moisture in the top soil layers was practically impossible in this soil type.



Alternate wetting and drying techniques are likely to result in water savings without yield penalties in locations where the ground water table is not too low so that roots can easily access soil moisture from lower levels. Riverside depressions or large irrigation schemes with a low groundwater table would be landscapes that match these criteria. Belder et al. (2004) suggest that irrigation water input can be saved by up to 15 % without affecting the yield when the groundwater table remains shallow (not deeper than -30cm). Soil texture is also likely to affect the water saving potential under water saving techniques with finely textured soils having a higher potential than more coarsely textured soils (Tabbal et al. 2002; Belder et al. 2007).

5 Conclusions and recommendations

The world faces many challenges like population growth, persistent poverty and malnutrition, changing diets, increasing migration and urbanization, increasing water scarcity, climate change, the increasing role of bio-fuel production in agriculture, and the need for environmental restoration in some areas. Globally, rice is the most important staple crop and therefore crucial for food security.

Global rice yields range from less that 1 t per hectare (t/ha) from poor rainfed cropping systems to as much as 10 t/ha from irrigated and intensive temperate region rice cultivation. But an estimated area of 15–20 million hectares of irrigated rice will be affected by water scarcity, threatening the livelihoods of many farmers, mainly small scale farmers since virtually all rice in sub-Saharan Africa and Asia is produced on land holdings of less than three hectares. Different water saving rice cropping methods have been developed, but their broader ecologic and socio-economic outcomes remain unclear. Therefore, the present study reviews the scientific literature and compiles findings that contribute to fill the knowledge gap on input use and environmental and socio-economic outcomes of selected rice cropping systems: the System of Rice Intensification (SRI), Alternate Wetting and Drying (AWD) (and its site specific adaptations), and dry seeded rice or aerobic rice. The study briefly presents the special features of these rice cropping systems before addressing the following subjects: water use and water productivity, energy consumption, labor requirements and gender aspects, fertilizer use, weed occurrence and pesticide use, grain yields, production economics and impact on poverty, environmental impacts (ammonia volatilization and soil fertility).

Water savings can be achieved without yield penalties by reducing the losses of nonproductive water outflows from the rice field, in particular seepage and percolation. However, the research results show a broad range of possible water savings (from 11.5 % up to 63.7 %) and conflicting figures on changes in water use efficiency (from decreases of 30 % to improvements of up to 91 %) (Table 20). Results appear to be site specific and affected by seasonal variation.

Table 20 Differences in water use and water use efficiency of different rice cropping systems

	Country	Differences in		Source
		water use	water use efficiency	
AWD vs. conv.	China	-57.4 % to -63.7 %	50.8 % to 70.9 %	Xu et al. 2012
Aerobic vs. conv.	Philippines	-11.5 % to -50.7 %	32 % to 88 %; 0 % to 45 %; -6 % to -30 %	Bouman et al. 2005
SRI vs. conv.	China	-57 %	91 %	Zhao et al. 2010
SRI vs. best management practice	Senegal	-16 % to -48 %	13 % to 81 %	Krupnik et al. 2012

The reduction of irrigation water input needed at the field level depends on the status of the ground water table. High water savings at the field level can be achieved if surrounding fields are continuously flooded, hence replenishing the groundwater table like in many experimental settings where high water savings could be achieved. Water use efficiency varies with the rice variety and provides scope for breeding varieties for water scarce environments. The existence and control of an irrigation system in terms of the amount and timing of water inflow by individual farmers is crucial for agronomic and economic success of rice production under water saving techniques. SRI is by no means the only approach to save water without affecting the yield (Krupnik et al. 2012a). Special care must be given to land leveling (e.g. by laser technology).

The differences in energy use of various water saving rice production systems is poorly studied up to date. Generally it seems that rice production consumes the largest amounts of energy compared to other major cereal crops (maize and wheat) but different yield levels (worldwide ranging from less than 1 t/ha to up to 10 t/ha) make generalizations on energy input to output ratios difficult. Most energy for rice cropping is utilized for fertilizer, followed by harvesting and seed, followed by irrigation. Tillage and plant protection use least energy. The reduction of seed required in SRI consists a considerable reduction of energy input. There seems to be agreement that rice cropping approaches without puddling use significantly less energy compared to conventional wet soil cultivation and more aerobic conditions will change the mechanization possibilities in rice cultivation because heavier and more energy efficient machinery can be utilized. Energy use patterns are thus likely to change with more aerobic soil conditions and require further investigation.

Labor requirements vary largely with as little time for rice cultivation as 25 person days reported from Brazil to up to 275 person days reported from India. Generally, SRI increases the amount of time spent for rice cultivation. Different methods for transplanting rice (at random, in line or square pattern assisted with either a rope or a wooden rake) exist some of which are more time consuming than others. However, the initially increased time for transplanting in SRI is reported to decrease after several seasons when farmers gain experience with the different handling technique. However farmers experience labor bottlenecks due to other on farm (other, higher value crops requiring their attention) or off-farm activities (wage labor).

The adoption of water saving technologies seems to change the gender involvement in rice cropping. However, gender dynamics are complex and highly location specific and development projects carefully have to assess existing gender roles and consider potential impacts. Depending on whether laborers are paid or unpaid workers, shifts in labor requirements can have positive or negative impacts. Possible differences in wages for men and women also have to be considered, like in the case of India.

The application of organic matter is recommended under SRI but its availability is often very limited. All rice cropping systems respond positively on the application of mineral fertilizer. Additional application of organic matter (e.g. as straw) showed improved N recovery from straw and mineral fertilizer under SRI leading to additive positive yield effects. N recovery from straw was more than 100% starting from the fifth season after application, suggesting that N was also taken up from the soil N pool. Integrated organic and mineral fertilizer applications had a positive effect on soil quality parameters and on partial macronutrient balances. However, farmers might prefer to apply the limited organic matter available to higher value crops like vegetables.

The type of crop establishment, water management, mechanical and chemical weed control management and their interactions affect the weed occurrence and species composition in rice fields. Influences and interactions are complex and are further complicated by site specificity. In general, a high water level in flooded rice fields is an effective means for controlling weed species. Due to the wider spacing combined with younger aged seedlings in SRI, the canopy of the rice crop takes longer time to close hence creating favorable growth conditions for weeds. The increased weed occurrence is a major problem of SRI. However, Krupnik et al. (2012b) did not find differences in weed biomass comparing SRI with recommended management practices. In the absence of mechanical options to control weeds, pesticide applications may significantly affect rice yields under SRI while pesticide applications do not affect conventional yields. However, whether farmers resort to pesticide depends on the pesticide price, the availability of sufficient amounts of pesticides in a timely manner and the existence of functioning local financial markets to provide credit.

Grain yields under different rice cropping systems vary largely due to site specific climate and soil conditions as well as different rice cultivars used. In general, when compared with high yield level cultivation methods, no significant difference with SRI yields was found, showing that the same yield can be achieved with less seed and less water. When comparing SRI, AWD, and other methods with farmers' cultivation practices, the improved methods outperformed farmers' yields.

High dosages of fertilizer that cannot be absorbed by the plants are lost to the soil, water and atmosphere leading to eutrophication, acidification and changes in biodiversity. Leaching of nitrogen from rice fields accounts for 30%-50% of N losses, 10%-30% are lost through denitrification, 30%-50% (10%-60%) are lost through ammonia volatilization. Ammonia volatilization is affected by climatic conditions, type of nitrogen fertilizer application, and field water management. Experiments show that the type of N fertilizer dominates ammonia volatilization compared to water depth. High ammonia volatilization losses occur mainly after fertilizer applications at the beginning of the cropping cycle, when the crop stand is not well established yet. Losses at this stage could be prevented using higher irrigation levels at early stages as suggested by Li et al. (2008), since higher water levels reduce ammonia volatilization (Freney et al. 1988; Williams et al. 1990). This practice was already implemented in the Senegal by rice farmers. However, they decided to start AWD at later growth stages of rice and kept their fields flooded at early stages mainly to suppress weeds. Although higher water levels can reduce ammonia volatilization, water depth has no significant influence on total N loss from the rice field.

Repeated wetting and drying as practiced in AWD and SRI increases soil pore volume, and repeated application of organic matter, e.g. rice straw as practiced in SRI increases total soil C and N contents, and soil microbial biomass, hence improving soil quality.

Farmers' top most constraints for adopting water saving technologies are (1) difficulties in land leveling, (2) difficulties in water control and management, and (3) shortages in labor availability. The three top most reasons to be interested in SRI adoption are (1) increases in yields compared to farmers' practice, (2) reduction in production costs, and (3) low initial investment. Least relevant reasons for farmers to adopt a water saving technology are ecosystem conservation, long term sustainability, and water savings. Farmers have no incentive to save water where irrigation water and electricity for pumping water are available free of charge (subsidized by governments).

Krupnik et al. (2012b) suggest using single and young seedlings only in low risk settings where farmers are able to minimize agronomic (e.g. land leveling) and social (e.g. labor availability) constraints (Krupnik et al. 2012b). In the farmer adapted practice, agronomic recommendations from SRI and recommended management practices were blended and farmers planted 3 seedlings per hill.

It can be concluded that circumstances affecting the required inputs and outcomes that can be expected under different water saving technologies are complex and highly site specific. Economic impacts of SRI adoption are very context specific and depend on micro-level socio-economic and agro-ecological conditions. The judgment on the overall performance of a water saving technology depends on the chosen reference base which can be either farmers' practice or the recommended best management practice. Adapting suitable agronomic practices to local conditions in collaboration with farmers proved to be the most successful option for improving rice cropping in terms of yields, water savings and other input use (Krupnik et al. 2012b).

There is a large variation in response to drought conditions among cultivars. This suggests that there is scope for the selection of cultivars that are suitable for water saving technologies (Bouman and Tuong 2000). New varieties have been developed that are more tolerant to water stress: e.g. aerobic rice, and Nerica (New Rice for Africa, by WARDA) (Bouman et al. 2007). Options to improve water productivity through breeding include 1) shorter growth duration combined with a higher yield of modern varieties which leads to lower water losses caused by evaporation, seepage, and percolation from individual fields and thereby to a higher water productivity related to total water input; 2) early vigor increasing the evapotranspiration efficiency. This leads to earlier canopy cover reducing evaporation from soil and weed suppression reducing weed transpiration.

The development or adaptation of weeding devices would help resolve the increased weed infestation in aerobic systems. Keen et al. (2012) point to the growing importance of precision mechanical weeding under aerobic rice cropping systems with increased weed occurrence. They also highlight that heavier tractors and harvesters are likely to be used under dry soil conditions compared to moist conditions because heavy machines are difficult to use on soft puddle soil. This should allow for higher work rates and labor output of machinery used in lowland rice cultivation. To further reduce the energy inputs from heavy machinery, the conversion of power into drawbar work by maximizing the tractive efficiency is of increasing importance (Keen et al. 2012).

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7 Annex

Table 21 **Area equipped for irrigation (percentage of cultivated land and part irrigated with groundwater)**

Continent Regions	Equipped area (million ha)		As % of cultivated land		Of which groundwater irrigation (2006)	
Year	1961	2006	1961	2006	Area equipped (million ha)	As % of total irrigated area
Africa	**7.4**	**13.6**	**4.4**	**5.4**	**2.6**	**18.5**
Northern Africa	3.9	6.4	17.1	22.7	2.1	32.8
Sub-Saharan Africa	3.5	7.2	2.4	3.2	0.4	5.8
Americas	**22.6**	**48.9**	**6.7**	**12.4**	**21.6**	**44.1**
Northern America	17.4	35.5	6.7	14.0	19.1	54.0
Central America and Caribbean	0.6	1.9	5.5	12.5	0.7	36.3
Southern America	4.7	11.6	6.8	9.1	1.7	14.9
Asia	**95.6**	**211.8**	**19.6**	**39.1**	**80.6**	**38.0**
Western Asia	9.6	23.6	16.2	36.6	10.8	46.0
Central Asia	7.2	14.7	13.4	37.2	1.1	7.8
South Asia	36.3	85.1	19.1	41.7	48.3	56.7
East Asia	34.5	67.6	29.7	51.0	19.3	28.6
Southeast Asia	8.0	20.8	11.7	22.5	1.0	4.7
Europe	**12.3**	**22.7**	**3.6**	**7.7**	**7.3**	**32.4**
Western and Central Europe	8.7	17.8	5.8	14.2	6.9	38.6
Eastern Europe and Russian Federation	3.6	4.9	1.9	2.9	0.5	10.1
Oceania	**1.1**	**4.0**	**3.2**	**8.7**	**0.9**	**23.9**
Australia and New Zealand	1.1	4.0	3.2	8.8	0.9	24.0
Pacific Islands	0.001	0.004	0.2	0.6	0.0	18.7
World	**139.0**	**300.9**	**10.2**	**19.7**	**112.9**	**37.5**
High-income	26.7	54.0	6.9	14.7	26.5	49.1
Middle-income	66.6	137.9	10.5	19.3	36.1	26.1
Low-income	45.8	108.9	13.1	24.5	50.3	46.2
Low-income food deficient	**82.5**	**187.6**	**16.6**	**29.2**	**71.9**	**38.3**
Least-developed	**6.1**	**17.5**	**5.2**	**10.1**	**5.0**	**28.8**

Source: FAO (2011)

Table 22 **Typical daily rates of water outflows and seasonal water input in lowland rice production in the tropics**

	Daily (mm per day)	Duration (days)	Season (mm)
Land preparation			
Land soaking			100 – 150
Evaporation	4 – 6	7 – 30	28 – 180
Seepage and percolation	5 – 30	7 – 30	35 – 900
Total land preparation			160 – 1580
Crop growth period			
Evapotranspiration			
Wet season	4 – 5	100	400 – 500
Dry season	6 – 7	100	600 – 700
Seepage and percolation			
Heavy clays	1 – 5	100	100 – 500
Loamy/sandy soils	15 – 30	100	1500 – 3000
Total crop growth			500 – 3700
Total seasonal water input			660 – 5280
Typical range of values for total seasonal water input		1000 – 2000	

Source: Tuong and Bouman (2003)

Table 23 Characteristics of selected indigenous rice varieties with yields reported to be higher than 6 t/ha, cultivated in India

Code	Variety name	Habitat	Duration (days)	Tillers/ plant	Panicle length (cm)	% Panicles	Grains/ panicle	Grain yield (t/ha)	Stress tolerance	Grain grade	Special features
AP-2	Lohondi	Lowland	150	17	25	90	200	6	1	2	1, F2, no need to parboil
PRG7	Rongochuri	Lowland	120	40	18	38	120	6.2	1, 3, 4	2	1, F1, Biryani making, grain elongation on cooking
CHP-1	Kalinga	Med Upland	90	25	20	90	200	6.2	1	2	1, Summer paddy, Rs 10/kg
CR-2	Jhumpuri	Lowland	160	32	30	93	290	6.2	1	2	1, Straw is strong, this is alternated with Champaisiari for avoiding weeds
DS-1	Asamchudi	Lowland	135	25	27	100	385	6.2	1, 3, 4	2	1, High satiety, rice porridge (Pejh, Amat), rice beer (Landah)
DS-12	Ramipareva	Med Upland	130	15	25	100	346	6.2	3, 4	2	1, 2, 3
GYPM-1	Puiri Lochai	Med Upland	125	43	24	100	275	6.2	1, 3, 4	2	1, Rs 12.5/kg
AP-1	Jeeraphul	Lowland	150	50	25	90	200	6.4	1	2	1, F2, no need to pairboil
SAM8	Tulsibas	Med Upland	135	21	29	13	355	3.5		2	F2, rice tate 50/kg, ratooning
DS-11	Bandiluchai	Lowland	135	23	NA	100	390	6.7	1, 3, 4	2	1, 3, 4, rice porridge (Pejh, Amat), grain elongation on cooking
PRG8	Sopori	Lowland	150	45	25	40	140	6.9	3, 4	3	F1, Ptha making, testes sweet
CR-1	Champaisiari	Lowland	160	35	32	95	320	7	2 (30d)	2	1, tasty, preferred by poor
GVK-1	Jauphur	Med Upland	145	70	19	100	280	7	1, 3, 4,	2	1, F2, Rice – 50/kg
SAM10	Sarogoto	Med Upland	135	26	29	23	350	7		3	1, fine non-scented rice, short-length straw suitable as fodder
SAM7	Mourikhas	Lowland	140	22	30	18	345	7		2	F2, rice –Rs 50-55/kg
SAM9	Khajurcheri	Med Upland	128	25	25	NA	245	7		3	1, fine non-scented rice, good as raw & parboiled, cross-pollinating cluster variety
CHP-3	Dhaniaphul	Lowland	140	45	25	90	330	7.2		1	1
KP-1	Bhataphul	Med Upland	95	25	28	100	300	7.2	1, 3, 4	1	1, F2
KP-2	Birholi	Med Upland	95	25	28	100	300	7.2	1; 3; 4	1	1, F2
CHP-6	Kumdhen	Lowland	110	25	25	25	250	7.4	1	2	1, F2
GYPM-2	Lal Lochai	Med Upland	125	33	23	100	250	7.4	1, 3, 4	2	1, Rs 12.5/kg
SSS-4	Kalajeera	Lowland	145	20	25	100	NA	7.4		1	1, F2
DS-13	Lolmokro	Lowland	135	15	27	100	271	7.5	1, 3, 4	2	1, F1, tasty
CR-6	Latamohu	Lowland	160	43	30	97	250	7.6	1	2	1
CR-8	Kalachampa	Med Upland	150	37	34	85	327	7.6	1	2	1
CHP-2	Kajiri	Lowland	135	45	25	90	285	8		2	1
DS-2	Kurulubuti	Lowland	135	19	26	100	271	8	1, 3 4	2	1, rice porridge (Pejh, Amat), less breaking while milling
SAM6	Radhatilak	Med Upland	135	21	29	17	345	8		2	1, F2, rice rate- Rs50/kg
CHP-4	Mahsuri	Lowland	125	55	25	90	285	8.4		2	1, tasty, Rs 10/kg
SS-7	Adanbargi	Lowland	100	35	28	90	225	8.8	1, 3, 4	2	1
SAM3	Agnilal	Med Upland	130	16	26	11	220	9	4 (Blast)	2	1, 7 -
SAM4	Red 1009	Med Upland	135	27	25	22	232	9		2	1, 2, 3, strong straw used for growing mushrooms and thatching
SAM5	Laluchura	Med Upland	130	25	29	18	245	9		2	1, 2, 4, bold variety preferred by economically-weaker sections, straw good for thatching
SS-5	Kanchan Safri	Med Upland	110	80	28	90	275	9.2	1, 3, 4	3	1
SS-6	Kumlichudi		120	45	28	90	275	9.2	1, 3, 4	2	1
SAM2	Sungibaram		130	21	29	18	285	10	4 (Blast)	2	1
SS-4	Bashabhog	Med Upland	120	43	32	90	350	10.4	1	2	1, F2
SAM1	Talomuli	Med Upland	130	31	30	18	280	11	1, 3	2	1, 4

Note: Stress tolerance- 1-Drought, 2-Flood, 3-Pests, 4-Diseases; Grain grade- 1-Round, 2-Bold, and 3-Slender; Special features- 1-Daily cooking, 2-Puffed rice, 3-Rice flakes, 4-Popped rice, 7-Medicinal, F1- Light-scented, F2-Strong-scented

Source: Banerjee (2013)

Table 24 Changes of grain yield of different varieties in the dry season (DS) and wet season (WS) of 2001–2003 comparing aerobic conditions with flooded conditions

Rice Type	Variety	Aerobic vs. flooded					
		2001		2002		2003	
		DS	WS	DS	WS	DS	WS
Upland	**Apo**	-13,8	-21,1	-22,8	-30,1	-41,2	-29,9
	IR43	-39,7	-14,1	-21,2	-6,4		
	UPLRI5					-44,4	-24
Lowland	**B6144F**	-33,8					
	IR73868H		-19,6				
	IR64			-33,9			
	Magat			-16,1	-23,4	-33,2	-24,5
LSD (0.05)							

Source: calculated based on Bouman et al. (2005)

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