CPWF Project Report

Developing a System of Temperate and Tropical Aerobic Rice in Asia (STAR)

Project Number 16

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1. ACKNOWLEDGEMENTS

This report presents the main results, outcomes, and impacts of CPWF project "Developing a System of Temperate and Tropical Aerobic Rice in Asia (STAR)" (PN16). The chapter "Project participants" lists the key partners and their institutions. However, many partners were involved in the project and it is impossible to name them all. Besides the key research staff, we'd like to especially thank all the students and scholars who were involved in the project and did a lot of the experimental work, the staff of experimental stations who took care of the experiments, the many staff of institutes and agencies who supported project activities (local government agencies, local stations, extension agencies, irrigation system officers), and – last but not least – the many farmers who participated in our on-farm trials, tested aerobic rice, and subjected themselves to "hours of interrogation" during field surveys!

Our CPWF project collaborated strongly and effectively with two research consortia and one other project on aerobic rice development in Asia:

1. The Irrigated Rice Research Consortium (IRRC), supported largely by a grant from the Swiss Development Agency (SDC).
2. The Consortium for Unfavorable Rice Environments (CURE), supported by different donors, including the CPWF through CPWF project 12.
3. The project on "Developing and Disseminating Water-Saving Rice Technologies in South Asia", supported by a grant from the Asian Development Bank.

We held joint planning meetings and workshops, and freely shared ideas, research strategies, protocols, and results.

Program Preface:

The Challenge Program on Water and Food (CPWF) contributes to efforts of the international community to ensure global diversions of water to agriculture are maintained at the level of the year 2000. It is a multi-institutional research initiative that aims to increase water productivity for agriculture—that is, to change the way water is managed and used to meet international food security and poverty eradication goals—in order to leave more water for other users and the environment.

The CPWF conducts action-oriented research in nine river basins in Africa, Asia and Latin America, focusing on crop water productivity, fisheries and aquatic ecosystems, community arrangements for sharing water, integrated river basin management, and institutions and policies for successful implementation of developments in the water-food-environment nexus.

Project Preface:

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CPWF Project Report series:

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2. PROJECT HIGHLIGHTS

The project "Developing a System of Temperate and Tropical Aerobic Rice in Asia (STAR) undertook strategic research to develop sustainable aerobic rice systems for water-scarce irrigated and rainfed environments in Asia. Aerobic rice is a production system in which specially developed rice varieties are grown in nonsaturated soils without ponded water just like wheat or maize. The target environments are areas where water is too short to grow conventional lowland rice, either rainfed or supplementary irrigated. In the Yellow River Basin of China, with a temperate climate, we have demonstrated that aerobic rice yields of 6 t ha^{-1} are attainable with about half of the water needed to grow lowland rice. In average rainfall years, farmers would need to give only 2-3 supplemental irrigations. The profitability is comparable with that of other food crops such as maize and soybean, depending on (yearly fluctuating) relative commodity prices (sometime profitability is lower, sometimes higher). Farmers like aerobic rice because it contributes to food self-sufficiency and requires less labor than transplanted lowland rice. It also allows them to diversify their cropping system. Moreover, aerobic rice can stand flooding and is an ideal crop for the large areas that get annually flooded by heavy rainfall or overflowing rivers that destroy the other crops. In the tropics, the development of aerobic rice is less advanced. In central India, in the Indo-Gangetic Plain, we identified rice varieties that can be grown in aerobic conditions, producing 4-4.5 t ha^{-1} and using 30-40% less water than lowland rice at the same yield level. In the Philippines, although yield potentials of 6 t ha^{-1} have been demonstrated, attainable yield ranged from 2.9 to 3.8 t ha^{-1} in the dry season, and from 3.9 to 4.5 t ha^{-1} in the wet season. A risk of yield decline was demonstrated at a few sites caused by soil-borne pests (such as nematodes), nutrient disorders, or a combination of both. In our sites in Northeast Thailand and Laos, breeding lines were identified with yield potentials of 2 (Thailand) to 3.5 (Laos) t ha^{-1}. Further research and development is needed to bring tropical aerobic rice to fruition, mainly on variety improvement (increasing yield potential and adaptation to aerobic soil) and sustainability. In conclusion, aerobic rice holds promise for those farmers in water-short irrigated or rainfed environments where water availability at the farm level is too low, or where water is too expensive, to grow flooded lowland rice.

3. EXECUTIVE SUMMARY

Background, objective, methods

New technologies need to be developed to assist farmers to cope with water shortages in rice production. Aerobic rice is a production system in which specially developed, input-response rice varieties with "aerobic adaptation" are grown in well-drained, nonpuddled, and nonsaturated soils without ponded water. Evidence of feasibility comes from northern China, where breeders have produced first-generation (temperate) aerobic rice varieties that use only 50% of the water used in lowland rice. However, sustainable crop-soil-water management recommendations are lacking. A shift from continuously flooded to aerobic conditions may have profound effects on sustainability (e.g., soil health), which needs study to develop sustainable production systems. Moreover, there are no aerobic rice varieties for the tropics. In this CPWF project, strategic research was undertaken to develop sustainable aerobic rice systems for water-scarce irrigated and rainfed environments in Asia. The objectives were to:

1. Identify and develop aerobic rice varieties with high yield potential
2. Develop insights into key processes of water and nutrient dynamics
3. Identify key sustainability issues, and propose remedial measures
4. Develop practical technologies for crop establishment
5. Characterize and identify target domains

Project partners and sites were located in the Philippines and in three CPWF benchmark basins: Yellow River, Indo-Ganges, and Mekong. Research methodologies included pot experiments, on-station and on-farm field experiments, simulation modeling, GIS, and farmer surveys.

Results and conclusions

Breeding of aerobic rice varieties is most developed in China, and varieties were identified with demonstrated yield potentials of 6 t ha^{-1} (HD502, HD297), in relatively dry soil with soil water tension going out of the 100 kPa measurement range. In India, tropical aerobic rice varieties with 4.5 t ha^{-1} yield potential were identified (Pusa Rice Hybrid 10, Proagro6111, Pusa834, Apo (PSBRc9), and in the Philippines of 6 t ha^{-1} yield potential (Apo, UPLRi5, Magat). However, these varieties had a relatively lower tolerance to dry soil conditions than the Chinese varieties in that soil water tensions had to stay below 30-40 kPa to reach these high yields. Under rainfed conditions in Laos and NE Thailand, breeding lines were identified with yield potentials of 2 (NE Thailand) to 3.5 (Laos) t ha^{-1}.

At Beijing, maximum aerobic rice yields of HD297 in controlled field experiments were 5-5.6 t ha-1 with 600-700 mm total irrigation plus rainfall water. Yields were 2.5-4.3 t ha-1 with 450-550 mm water input, while yields dropped to 0.5 t ha^{-1} in very dry soil (water tension higher than 100 kPa) around flowering, which increased spikelet sterility. Irrigation is essential at flowering time if there is no rain. The average seasonal evapotranspiration (ET) requirement was 600 mm. With shallow groundwater, capillary rise can meet most of the ET and there may be no need to irrigate. With deep groundwater tables, the net irrigation needs are 167 mm in a typical 'wet rainfall year" (2 times irrigation), 246 mm in a typical "average rainfall year" (3 times irrigation), and 395 mm in a typical "dry rainfall year" (4-5 times). Simulations showed that, on typical freely-draining soils of the YRB, aerobic rice yields with HD297 can reach 6 t ha^{-1}, with 477 mm rainfall and 112-320 mm irrigation water. The application of any amount of fertilizer N either reduced yield or kept yield at the same level as without N fertilization. Farmers' fields in northern China may have been over fertilized for many years to the extent that they are now 'saturated' with N. Moreover, they may receive large amounts of N through atmospheric deposition. Nitrogen omission in aerobic rice-wheat cropping systems in Mencheng County caused a marked decline in yield of both aerobic rice and winter wheat, whereas P and K omission had less effect. P and K became yield limiting for winter wheat, because of a higher demand for nutrients by winter wheat than aerobic rice.

At Delhi, aerobic rice in field experiments yielded more than 4 t ha^{-1} when irrigated at 40 kPa soil water tension in the root zone. Compared with typical amounts of water applied to lowland rice fields (under alternate wetting and drying), the amounts applied in the aerobic rice experiments of 780-1324 mm (irrigation plus effective rainfall) translated into 30-40% water savings for production levels of 4-4.5 t ha^{-1}. The fertilizer application rates in the experiments were 150 kg N ha^{-1}, 60 kg P ha^{-1}, and 40 kg K ha^{-1}.

In the Philippines, maximum experimental yields of variety Apo in the dry season ranged from 2.9 to 3.8 t ha^{-1}, with the exception of 1 site/year when yields went up to 5.4-6.1 t ha^{-1}. There was hardly any effect of irrigation water application rate because at most sites, shallow perched water tables developed during the experiments that reached up and into the root zone, keeping soil water tensions within 0-30 kPa. Therefore, high yields were realized with as little as 274-590 mm total water input. Yield responded positively to fertilizer N applications, with an application of 120 kg ha^{-1} sufficient to reach maximum yields. In the wet season, soil water tensions in the root zone were mostly between 0-15 kPa, because of heavy rainfall and shallow groundwater tables. Maximum yields were 3.9-4.5 t ha^{-1}. Fertilizer N addition increased yields, and the amount needed for high yields varied from 60 to 120 kg N ha^{-1} across sites. Crops lodged at some sites with 120 and 150 kg N ha^{-1} because of heavy winds and strong rains. The risk of lodging needs to be included in formulating fertilizer N recommendations.

The few experimental results in Laos (1 year, 2 sites) show a large variability in nutrient response among sites.

In the long-term aerobic rice experiment at IRRI, yield of Apo under continuous aerobic conditions declined (relative to flooded conditions) during the first 10 seasons, but increased again afterwards (in the dry season). The yield in the same year in a "new" aerobic field (after continuous flooded cropping) was 2.5 t ha^{-1} higher than in a seventh-season continuously cropped aerobic field. Levels of the *Meloidogyne graminicola* nematode were high, but the typical patchiness related to the occurrence of nematodes was not observed. The yield decline could be reversed by crop rotations (two seasons), fallowing (two seasons), and flooding (three seasons). Yield decline could not be reversed by the application of micro-nutrients, P, or K. However, crop growth was consistently improved by the application of N fertilizer in the form of urea or Ammonium sulfate, with the latter being much more effective than the first. Beside the gradual yield decline under continuous cropping of aerobic rice, we encountered two cases of "immediate yield collapse" in fields cropped to aerobic rice for the very first time in the Philippines. Despite large amounts of irrigation water input and large doses of fertilizer N, yields failed completely. Preliminary evidence of genotypic variation in response to "soil sickness" was found.

Direct dry-seeded aerobic rice is not very responsive to row spacing and seed rate (within the limits tested). Row spacings between 25 and 35 cm, and seeding rates between 60 and 135 kg ha^{-1} generally gave the same yields in China and the Philippines. In India yields declined fast with seeding rates below 40 kg ha^{-1}. In practice, the "unresponsiveness" of aerobic rice to seed rate and row spacing means that farmers are rather flexible in choosing their own seed rates and spacings.

Aerobic rice holds promise for farmers in water-short irrigated or rainfed environments where water availability at the farm level is too low, or where water is too expensive, to grow flooded lowland rice. When the percolation losses in flooded rice are 3.5 mm d^{-1} or higher, aerobic systems with flash-flood irrigation will require less water, and if the percolation losses are 0.5 mm d^{-1} or lower, only aerobic systems with sprinkler irrigation require less water. In northern China, the target areas are where water availability is 400-900 mm during the cropping season. In the central part of the YRB, yields of 5-6 t ha^{-1} are attainable with 0-220 mm irrigation application (in average rainfall years; groundwater 2 m deep or less). In these regions, farmers who currently try out aerobic rice attain usually 3-4 t ha^{-1}, with 150-220 mm supplementary irrigation. With these yields, financial returns to aerobic rice can be more or less than to upland crops (maize, soybean), depending on relative market prices (that fluctuate among years). Reasons for adoption are: having own rice on the farm, ease of establishment and less labor needs (compared with lowland rice), good eating quality. Negative views are: low yields, difficult to control weeds, insufficient extension support, difficult to market. Aerobic rice is unique in its characteristics to withstand both flooding and dry soil conditions, which make it an ideal crop for areas prone to surface flooding where other crops would suffer or fail.

Impacts

Four international journal papers have been published, seven are submitted or in advanced stage of preparation, three international journal papers include parts of our CPWF results, and twelve national journal papers, book or proceeding chapters are published. More than 20 posters have been presented, and oral presentations made at workshops, conferences, and other fora. We organized an international Aerobic Rice workshop in Beijing, October 22-25, 2007, which attracted about 100 participants.

Twenty-two graduate and undergraduate students were involved in the project, and most of them have completed their theses. Aerobic rice was part of 32 training courses on water management in rice production systems organized conjunctively by the Water Workgroup of the Irrigated Rice Research Consortium and the CPWF project. In total, an estimated 1589 professionals received training on aerobic rice. Through farmer school days and field demonstrations, an estimated 1875-3750 farmers were reached with information about aerobic rice.

The major impact of aerobic rice at farm household level is that it offers farmers the choice to grow rice when water is too scarce to grow lowland rice, and allows them to diversify their cropping system which will augment resilience and increase overall sustainability. Adoption will (among others) depend on relative market prices the different crops available to farmers are expected to fetch in a particular year, the degree of water scarcity, availability of quality seeds and extension support, and – last but not least – farmers' preference to grow their own rice for self sufficiency rather than depending on markets.

Extrapolation domain construction and scenario analysis (by CPWF-Impact Study) suggest that aerobic rice can have large impacts in India and countries in the lower parts of the Mekong Basin. Most of the impacts would occur from adoption in India and Thailand and would include increased yields, production, and area grown to rice, reduced rice prices, and reduced levels of child malnutrition. The IMPACT-WATER model founds that India will be a net importer of rice in 2050. Adoption of aerobic rice would reduce the amount of required imports, which could be very important if climate change stresses rice-growing areas in the tropics and reduces the amount of rice available for trade.

Key recommendations

The aerobic rice technology can be considered sufficiently mature for dissemination in the Yellow River Basin (YRB), but not so for most of tropical Asia where more R&D is needed to create sustainable and high-yielding aerobic rice systems. "Aerobic rice" should be recognized as a special crop type besides "lowland rice and "upland rice" to facilitate the collection of statistics on adoption and spread of aerobic rice, and to encourage extension agencies to address aerobic rice. In the YRB, local and national governments should strengthen the formal and informal extension system at all levels. In most of tropical Asia, preference should be given to setting up dedicated aerobic rice breeding programs and strengthening the R&D capacity to develop sustainable production systems. Further research should focus on increasing the yield potential and attainable yield at farm level through breeding and improved management (especially nutrients), quantifying real evapotranspiration rates and extrapolating field-level water savings to regional scale, inventorizing soil health issues in the target domains, establishing long-term continuous cropping experiments to address sustainability issues, understanding and solving the phenomenon of yield collapse as observed at some sites in the Philippines, and understanding the biophysical and socio-economic factors that lead to adoption by farmers

4. INTRODUCTION

Rice is the staple food in Asia but also the single biggest “user” of fresh water. It is mostly grown under submerged soil conditions and requires much water compared with other crops. The declining availability and increasing costs of water threaten the traditional way of irrigated rice production. Moreover, lack of rainfall is a major production constraint in rainfed areas where many poor rice farmers live. An efficient use of water is critical to help reduce poverty and safeguard food security in water-scarce areas in Asia.

Water requirements can be lowered by reducing water losses by seepage, percolation, and evaporation. Promising technologies include saturated soil culture, intermittent irrigation, and the system of rice intensification. However, these technologies still use prolonged periods of flooding, so water losses remain high. A fundamentally different approach is to grow rice like an upland crop, such as wheat, on non-flooded aerobic soils, thereby eliminating continuous seepage and percolation and greatly reducing evaporation. Traditional upland rice has been bred for unfavorable uplands to give a stable though low yield under minimal external inputs. Previous experiments of growing high-yielding lowland rice under aerobic conditions have shown great potential to save water, but with a severe yield penalty. A new type of rice is needed to achieve high yields under high-input aerobic conditions.

Evidence of feasibility comes from northern China, where breeders have produced first-generation (temperate) aerobic rice varieties with a high yield potential using less water than lowland rice. However, initial high yields are difficult to sustain and yields may decline after 3–4 years of continuous cropping. There are no aerobic rice varieties for the tropics and crop-soil-water management recommendations are lacking. A shift from continuously flooded to aerobic conditions may have profound effects on sustainability (e.g., soil health). We also need to deepen our understanding of the potential target domains along with the biophysical and socioeconomic circumstances of the farmer beneficiaries.

In this CPWF project, strategic research was undertaken to develop sustainable aerobic rice systems for water-scarce irrigated and rainfed environments in Asia. The project lasted from October 2004 to March 2008. Project partners and sites were located in different countries in three of the CPWF’s benchmark basins and in the Philippines (Table 4.1; chapter “Project participants”). This report presents the results, outputs, outcomes, and (initial) impacts. The results and outputs are reported by objective (see next chapter). We also specified the activities undertaken, and results achieved, by country to easily extract the outputs per benchmark basin.

Table 4.1. Country partners by CPWF benchmark basin and relative weight of activities.

CPWF benchmark basin	Project partner country	Weight (%)
Yellow River	China	45
Mekong	Laos, Thailand	5
Indo-Gangetic	India	20
Other	Philippines	30

5. OBJECTIVES

The goal is to ensure food security and increase sustainable livelihoods in rural and urban Asia, by easing water scarcity as a constraint to agriculture, economic development, and nature conservation. The objectives are to develop prototype aerobic rice production systems for water-scarce environments, by which farmers grow rice as a dry-field crop in irrigated, or rainfed, but non-flooded fields, achieving high yields while sharply reducing their water use and non-productive outflows. Specifically, to

1. Identify and develop aerobic rice varieties with high yield potential (Aerobic rice varieties identified)
2. Develop insights into key processes of water and nutrient dynamics that allow us to derive prototype management practices (water and nutrient dynamics).
3. Identify key sustainability and environmental impact issues, and propose remedial measures, such as crop rotations (sustainability)
4. Develop practical technologies for crop establishment (originally, “weed control” was included but dropped in favor of more focus on establishment)
5. Characterize and identify target domains and quantify the potential amounts of water savings and rice production (target domain)

In China, aerobic rice varieties have been developed since the mid-eighties and emphasis was put on objectives 2-5. In the Philippines, IRRI runs an aerobic rice breeding program and, like in China, emphasis was put on objectives 2-5. In India, variety screening for aerobic conditions was initiated in 2001. We continued variety screening (objective 1) and moved into objectives 2 and 4 by combining variety screening with water and seed rate experiments. In Thailand and Laos, no screening for aerobic conditions was done before, and we focused mainly on objective 1 with some on-farm testing with different management conditions in Thailand (objective 4).

6. OUTCOMES AND IMPACTS

All field experiments and screening trials had 3 or 4 (mostly) replications, and statistical analyses are provided as much as possible (in a few cases only, no statistical analyses were reported by project partners). Throughout the report, all yields are expressed at 14% moisture content, and refer to rough rice (nunhusked and unmilled). Total biomass is expressed at 0% moisture content after oven-drying. In the method sections, we summarize the treatments and site descriptions on main lines only for brevity sake; full experimental details are available on request or are reported in journal papers listed at the end.

6.1. Objective 1: Aerobic rice varieties identified

6.1.1. Method

Actual breeding of aerobic rice varieties was not part of the project, but we "tapped' into ongoing breeding activities and focused on selection and evaluation of breeding lines and varieties at our project sites in potential target domains. We participated in advanced breeding trials and multi-location testing, and conducted our own field experiments and participatory variety selection (Table 6.1.1).

Table 6.1.1. Sites of germplasm selection activities per country

Activity/country	Philippines	China	India	Laos	Thailand
Advanced breeding trials	Los Banos, Dapdap	Various locations in N China		Sanasomboun, Phonethong, Saythany	
Multi-variety field experiments	Munoz, San Ildefonso, Dapdap, Los Banos		Delhi		Udon Thani, Khon Kaen, Ubon Rachathani
Farmer-participatory selection	San Ildefonso		Secunderabad (Bulandshahar)		Nong Khai, Mahasarakham, Phimai

For each country or site, either released varieties or breeding lines were identified with best local suitable were identified

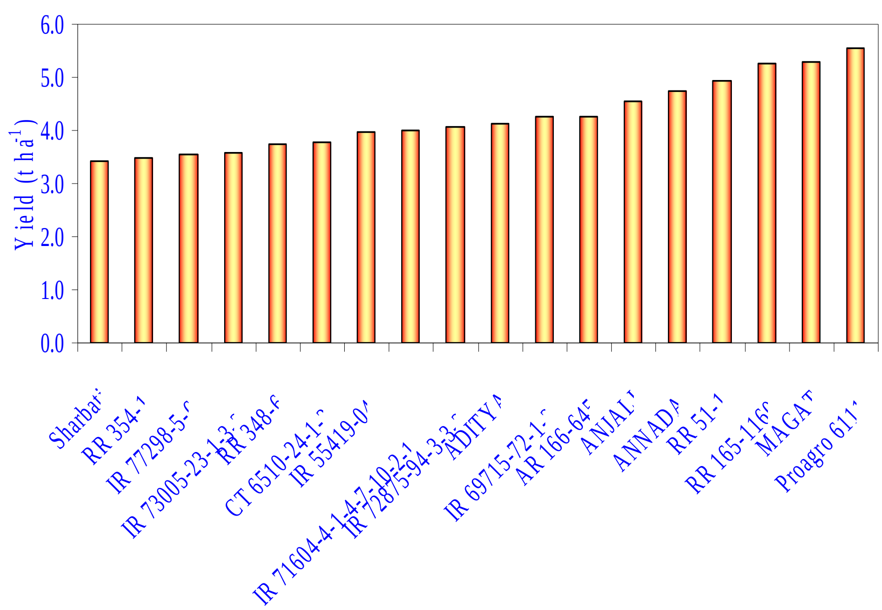
6.1.2. Results China

CAU runs a special aerobic rice breeding program and we used promising materials for testing at our project sites A large number of varieties are identified for northern China, depending on local climate and cropping systems. Between 1986 and 2005, 58 aerobic rice varieties have been released (though classified as "improved upland rice"). In our experiments, yields of up to 6 t ha^{-1} were obtained with HD502 and HD297 in aerobic soil with soil water potentials at 20 cm depth going beyond 100 kPa.

6.1.3. Results India

We summarized the results of screening trials of several promising lowland and upland genotypes/hybrids from India and IRRI under soil water conditions kept close to field capacity in 2001-2004. Rice genotypes Anjali, Annada, IR55419-04, Magat, Proagro 6111, RR 165-1160, RR 51-1, Pusa Rice Hybrid 10, Proagro6111 (hybrid), Pusa834 and IR55423-01 (Apo1) yielded more than 4.5 t ha^{-1} (Figure 6.1.1).

Figure 6.1.1. Yield of highest-yielding genotypes under aerobic soil conditions kept close to field capacity, IARI-WTC station, Delhi, 2001-2004.

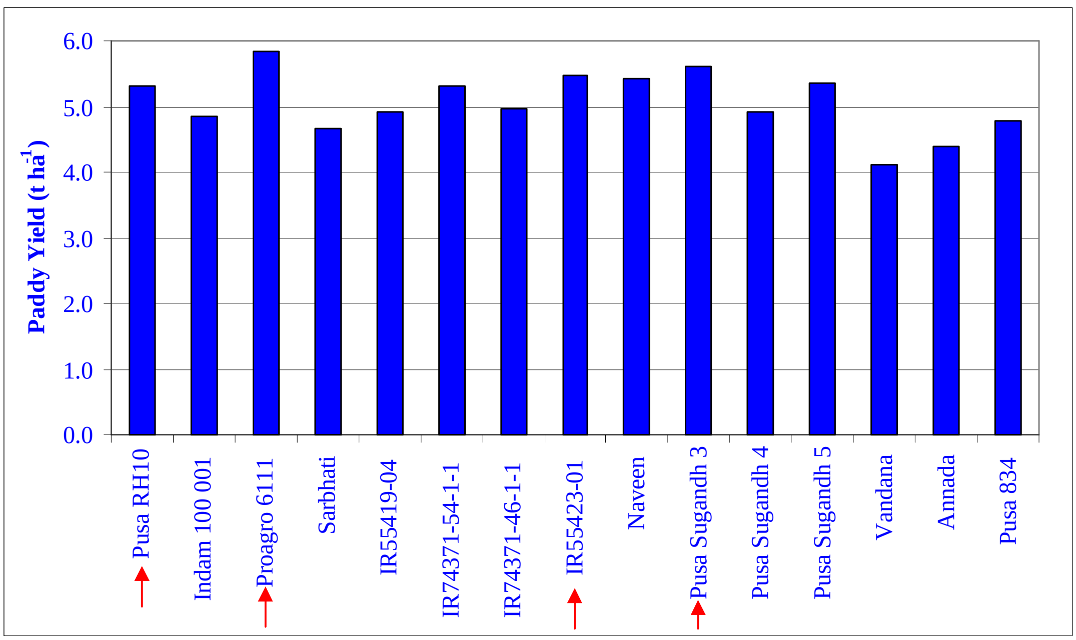


In 2005-2006, we extended the variety testing to three different soil water regimes (soil close to saturation, irrigation at 20 kPa soil water tension in the root zone, and irrigation at 40 kPa soil water tension in the root zone) and included new genotypes. The details of these trails are reported in the paragraph "Water and nutrient dynamics" below. We concluded that rice genotypes

Pusa Rice Hybrid 10, Proagro6111 (hybrid), Pusa834 and IR55423-01 (Apo1) were highly tolerant to aerobic conditions, as they produced grain yields of more then 4 t ha^{-1} under aerobic production system irrigated at 40kPa soil moisture tension in both the seasons (*Kharif* 2005 and *Kharif* 2006).

In 2005-2006, we also tested genotype in farmer Participatory variety selection (PVS) trials in Secunderabad, Bulandshahar. The hydrologic conditions such as soil water tension and groundwater table depth were not recorded. An example of results obtained in 2006 is given in Figure 6.1.2. The yields of the tested rice genotypes under aerobic rice conditions were similar to yields obtained by farmers in the region using transplanted rice under conditions of alternate wetting and drying. Among the 15 varieties evaluated in the PVS trial, farmers selected Proagro 6111, Pusa Rice Hybrid 10, Apo (IR55423-01) and Pusa Sugandh 3 based on their yield under aerobic conditions, grain fineness, and higher market price.

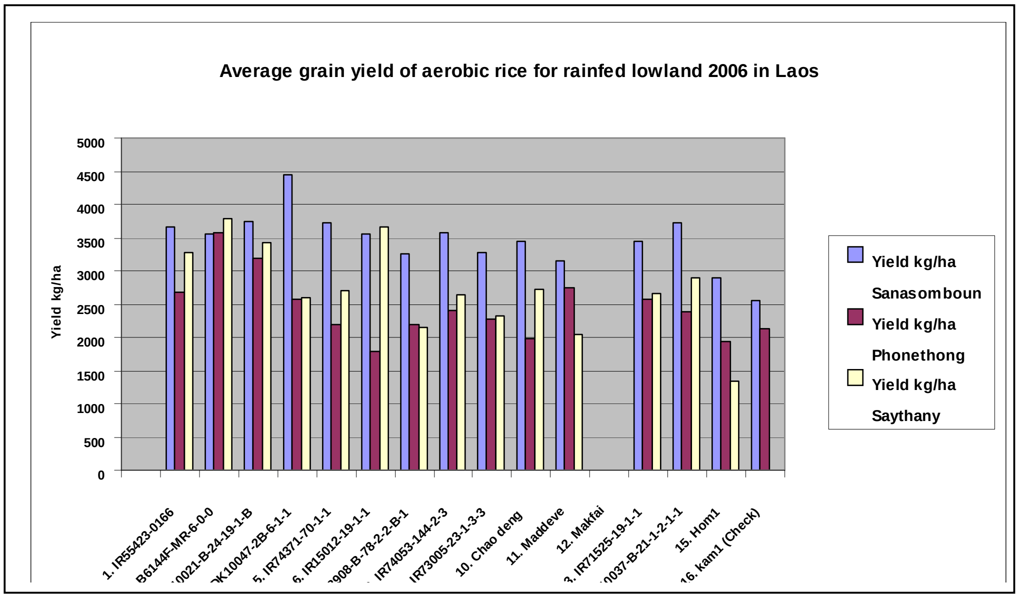
Figure 6.1.2. Yield of various genotypes grown in farmers' fields (PVS trials) under aerobic conditions, Secunderabad, Bulandshahar, 2006.



6.1.4. Results Laos

Screening of varieties suitable for aerobic conditions started in Laos with the STAR project in 2005. Screening trials were carried out in two environmental conditions: one site in the upland rainfed environment and two other sites on upper toposequence positions in rainfed lowland areas with uncertain water supply (both sites rainfed). A number of 16 to 24 genotypes were selected from a drought prone screening program, eight of them were traditional varieties selected from upland condition, whereas the others were promising new lines including two improved varieties TDK3 and TDK7 and two traditional varieties Hom1 and Kam11. Four lines, IR55423-0166, B6144F-MR-6-0-0, TDK10021-B-24-19-1-B, andTDK10047-2B-6-1-1, recorded yields in excess of 3 t ha^{-1} under, while B6144F-MR-6-0-0 had a constant and significantly superior yield performance of 3.6 t ha^{-1} at all three locations. Figure 6.1.3 gives the yield measured in 2006. No soil water tensions were measured in the screening trials.

Figure 6.1.3. Yields of different genotypes tested at three locations in Laos, 2006 wet season.



6.1.5. Results Thailand

Screening of varieties suitable for aerobic conditions started in North-East Thailand with the STAR project in 2005. Promising local improved upland varieties and aerobic rice varieties from IRRI were tested at a number of target locations in NE Thailand on-farm and on-station throughout 2005-2007. Most materials were tested under rainfed conditions and a large variability in yields was obtained across sites and years. No soil water tensions were measured in the screening trials. Like in Laos where screening for aerobic rice varieties started only recently, yields were much lower than in China, Philippines, or India, Tables 6.1.1-6.1.3. Under flooded conditions, yields could go up to 5 t ha^{-1}, but they dropped to 2 t ha^{-1} and below under most rainfed conditions (even with 2074 mm at Nong Khai in 2005, Table 6.1.1).

Table 6.1.1. Grain yield of various cultivars under rainfed conditions in farmers' fields at Nong Khai, Mahasarakham, and Phimai, Thailand, 2005. Total seasonal rainfall was 2074 mm at Nong Khai, 711 mm at Mahasarakham, and 479 mm at Phimai.

Cultivar	Grain yield (t ha^{-1})		
	Nong Khai	Mahasarakham	Phimai
SKN	1.1	2.0	0.5
SPT1	0.8	1.0	0.2
RD10	1.0	1.3	0.1
SMJ	0.6	1.9	1.1
UBN92110	-	1.1	-
UBN91051	-	-	0.3
Rai Nonsung	-	1.7	-
RD15	-	-	0.3
HY71	1.4	-	-
Irrad SMJ	1.2	-	-
Local var	-	1.8	0.0
Mean	1.0	1.5	0.4
SED	0.2	0.1	0.1

Table 6.1.2. Grain yield and days to flowering (DTF) among rice lines, at Udonthani Rice Research Center (UDN) and Khon Kaen Rice Research Center, Thailand, 2005. Seasonal rainfall was 627 mm at Khon Kaen.

	Grain yield (t ha^{-1})			
	UDN (flooded)		KKN (Rainfed)	
Cultivar	Grain yield (t/ha)	DTF (days)	Grain yield (t/ha)	DTF (days)
SKN	3.80	87	0.83	102
SPT1	5.10	96	0.30	121
RD10	5.10	96	0.34	120
SMJ	2.40	77	0.79	103
Standard error	0.20	0.3	0.06	0.7

Table 6.1.3. Yield and days to flowering of different genotype groups, evaluated under three growing conditions (flooded, rainfed, and flooded with drought at flowering) at Ubon Ratchathani Rice Research Center, Thailand, 2006.

	Grain yield (t ha^{-1})			Days to flowering (days)		
Genotype group	Flooded	Rainfed	Drought	Flooded	Rainfed	Drought
Rainfed (IRRI)	2.3	2.2	1.3	90	87	95
Irrigated (IRRI)	2.3	2.2	1.3	91	83	96
Aerobic (IRRI)	2.1	2.3	1.7	82	75	86
Upland (IRRI) 1	1.9	1.7	0.9	88	86	97
Upland (IRRI) 2	2.1	2.1	1.3	89	80	94
Aerobic Med	2.1	2.1	1.5	86	79	90
RF (Thai)	1.7	2.0	1.2	84	86	89
Upland (Thai)	1.5	1.7	1.7	84	91	88
Regional check	1.7	2.0	1.2	84	91	88
Mean	2.0	2.0	1.3	86	84	91
Max	2.3	2.3	1.7	91	91	97
Min	1.5	1.7	0.9	82	75	86
lsd0.05	0.2	0.2	0.1	1	1	1
CV	24.40	21.54	22.05	3.90	3.35	2.29

6.1.6. Results Philippines

IRRI runs a special aerobic rice breeding program and we used promising materials for testing at our project sites. Under aerobic soil condition with irrigation applied at thresholds of 20-40 kPa soil water tension at 20 cm depth, the following varieties have yield potentials of around 5-6 t ha^{-1}: “Apo” (PSBRc9), UPLRI5, PsBRc80. Sporadically, yields of more than 6 t ha^{-1} have been obtained with soil water tensions below 20 kPa. The hybrid variety Magat is liked by farmers but found too expensive (seed costs).

6.1.7. Conclusion

Breeding of aerobic rice varieties is most developed in China where aerobic rice varieties have been released since 1985. Although yield potentials of 7-8 t ha^{-1} are mentioned in various Chinese sources (Wang Huaqi, 2002), we obtained maximum yields of 6 t ha^{-1} in the STAR project under well defined experimental conditions. The tested varieties (HD502, HD297) tolerated relatively dry soil conditions with soil water tension going out of the 100 kPa measurement range. The Chinese varieties being released for the N China Plain are not suitable for tropical conditions such as found in the Philippines, Laos, and Thailand, but may be suitable for northern India. In the Philippines, tropical aerobic rice varieties with the same yield potential (around 6 t ha^{-1}) as in N China have been identified, but with much lower tolerance to dry soil conditions (i.e., water tensions had to stay below 40 kPa to reach the high yields). Further breeding efforts need to focus on increasing the tolerance to dry soil conditions while maintaining yield potential. Under similar soil water conditions as in the Philippines, screening of varieties in India has resulted in the identification of germplasm (not all stable varieties yet) with a yield potential of 4-5 t ha^{-1}. Under rainfed conditions in Laos and NE Thailand, first screening of germplasm (without a dedicated aerobic rice breeding program to choose from) has identified material with yield potentials of 2 (NE Thailand) to 3.5 (Laos) t ha^{-1} yields under rainfed or irrigated aerobic conditions.

6.2. Objective 2: Water and nutrient dynamics

Water and nutrient dynamics were studied in on-station and on-farm field experiments and with simulation modeling. Here, we report on these activities separately. Following Tuong et al. (2005), we computed crop water productivity with respect to combined irrigation water input and rainfall (WP_{IR}):

$$WP_{IR} = \frac{\text{Grain yield}}{\text{Irrigation + rainfall}} \qquad \text{(kg grain m}^{-3}\text{ water)}$$

6.2.1. Field experiments

6.2.2. Method

We analyzed and synthesized field experiments we performed in the years before the STAR project actually started, and performed new experiments during the STAR project itself. Table 6.2.1 gives an overview of the location of the experiments.

Table 6.2.1. Sites of water and nutrient field experiments per country

Activity	Philippines	China	India	Laos	Thai
Water, N Water x N	San Ildefonso, Munoz	Beijing: Changping, Shanzhuang	WTC-IARI station, Delhi		
N x row spacing	San Ildefonso, Dapdap, Munoz				
N,P,K		Shuanghu (Mencheng)		Houay Kot, Somsanouk	

In *China*, water and nitrogen (N) experiments done near Beijing were synthesized for the period 2001-2006. In all these experiments, the aerobic rice variety HD297 was direct dry seeded, with 3-5 irrigation water treatments aiming at different amounts applied and distribution over the cropping season. In Changping, we had irrigation water treatments in 2001-2002, and irrigation by various N treatments in 2003-2004 (N details in Table 6.2.2). In Shangzhuang, we had 3 irrigation by 3 N treatments in 2005-2006. The N treatments were 0 (N0), 75 (N1) and 150 kg fertilizer-N ha^{-1} (N3). The soil at Changping was sandy (80% sand, 13% silt, 7% clay) down to 2 m, with a groundwater table deeper than 20 m. The soil at Shangzhuang was more loamy (60% sand, 30% silt, 10% clay) down to 1 m, with groundwater depth fluctuating between 0 and 1.2 m. At all sites in China, irrigation water was applied by flash-flooding. At Shangzhuang, we introduced a third treatment factor in 2006: seeding rate. Whereas in 2005, the seeding rate was 135 kg ha^{-1}, in 2006 we used 135 kg ha^{-1} in the treatment combinations of W1 and W3 by N0 and N2, whereas we used a reduced seeding rate of 65 kg ha^{-1} in all water x N treatment combinations. Full experimental details of the Beijing experiments are given by Yang Xiaoguang et al. (2005), Bouman et al. (2006), Xue et al. (submitted, 2007), and Limeng Zhang et al (in prep 2008).

We computed evapotranspiration rates from the soil water balance in the wettest soil water treatments, using measured data for inputs (irrigation, rainfall) and changes in soil water content from installed neutron probes, for our field experiments in Changping (we did not do this for Shangzhuang because of difficulties of estimating capillary rise from the shallow groundwater contribution to the soil water balance). We then computed net irrigation water requirements as seasonal evapotranspiration minus rainfall, for three types of rainfall years (wet, medium, dry) derived from 50 years of weather data at Changping.

Table 6.2.2. Fertilizer N rates in field experiments at Changping, 2002-2004.

Year	Fertilizer N application (kg ha^{-1})
2002	none
2003; exp 1	0
	113
	150
2003; exp 2	225/3splits
	225/5splits
2004	0
	75
	125
	175
	225

In 2005-2006, nutrient experiments on nitrogen (N), phosphorus (P), and potassium (K) were undertaken in rice-wheat and wheat-rice rotations in a farmer's field in Shuanghu village (33°17' N, 116°33' E, 25 m asl), Mengcheng County, Anhui Province. The soil is classified as Fluvisol derived from river sediments, with 10% sand, 58% silt, and 32% clay. Groundwater depth was unknown at the start of the experiments. The cropping sequences were aerobic rice - winter wheat (AR-WW) from June 2005 to June 2006 and winter wheat - aerobic rice (WW-AR) from October 2005 to October 2006. Thus, the two aerobic crops were grown in succeeding years (2005 and 2006), while the two winter wheat crops were present during the same winter season (2005/2006). Fertilizer treatments were an optimal dose of N, P, and K (NPK), of P and K (PK, N omission), of N and K (NK, P omission), of N and P (NP, K omission), and of a control (CK) (Table 6.2.3). Aerobic rice, *cv*. Han Dao 502, was drilled at a rate of 45 kg ha^{-1} in 2005. Because of the low emergence rate in 2005 we increased the seed rate to 75 kg ha^{-1} in 2006. A surface irrigation of 60 mm was applied by flash flooding on June 16, June 22, and August 3 in 2005, and on June 11, June 17, August 8, and August 22 in 2006. Winter wheat (*cv*. Yumai 18) was sown on 23 October 2005 at a rate of 187.5 kg ha^{-1}. Full experimental details are given by Xiao Qindai et al. (in prep 2008).

Table 6.2.3. Fertilizer rates (kg ha^{-1}) applied to aerobic rice and winter wheat at Shuanghu, 2005 and 2006.

Treatments	Aerobic rice			Winter wheat		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
NPK	120	50	75	180	50	90
PK	0	50	75	0	50	90
NK	120	0	75	180	0	90
NP	120	50	0	180	50	0
Control	0	0	0	0	0	0

In India, field experiments focused on variety evaluation under different water regimes at the station of the IARI-Water Technology Centre at Delhi. In total, 12 varieties were screened in 2005, and 24 in 2006 and 2007. The three irrigation regimes were: irrigation water applied (through flash flooding) when soil water tension at 20 cm depth reached "0 kPa" which means keeping the soil close to saturation (I0), when soil water tension reached 20 kPa (I20), and when soil water tension reached 40 kPa (I40). The soil in the top 30 cm is a clay loam with 36% sand, 35% silt, and 29% clay. Groundwater is deeper than 2 m. In all experiments, the aerobic rice varieties were dry seeded at the rate of 80 kg ha^{-1}.

In *the Philippines*, we had water x N field experiments in the dry seasons of 2005-2007 at San Ildefonso (Bulacan), Munoz-PhilRice station, and Munoz-station of Central Luzon State University (CLSU). At all sites and in all years, tropical aerobic rice variety "Apo" (PSBRc-9) was direct dry seeded. The treatments were the same at all sites and all years: 4 fertilizer-N levels (0, 60, 120, and 165 kg N ha^{-1}) and 3 irrigation treatments (two times irrigation per week (W1), one time per week (W2), and one time in two weeks with extra irrigation from PI to flowering (W3)). At Munoz-CLSU, irrigation treatments were slightly different: fields kept around filed capacity (W1), irrigation applied at 75% of field capacity (W2), and irrigation applied at 50% field capacity (W3). At San Ildefonso, the soil was clay loam (25% sand, 37% silt, and 38% clay). The groundwater depth varied around 2 m, but during the experiments, a shallow perched water table developed that fluctuated between 0 and 0.7 m depth. At Munoz-PhilRice, the soil was clay (46% sand, 17% silt, and 37% clay). The groundwater depth fluctuated between 1.5 and 2 m, but during the experiments, a shallow perched water table developed that fluctuated between 0 and 0.5 m depth. At Munoz-CLSU, the soil was a clay loam (29% sand, 45% silt, and 26% clay). No information is available on the depth of groundwater. At San Ildefonso and Munoz-PhilRice, irrigation water was applied by flash-flooding, while at Munoz-CLSU, it was applied by sprinklers.

We had fertilizer N x row spacing experiments in the wet seasons (plus one experiment in the dry season 2005) of 2004-2005 at San Ildefonso (Bulacan), Munoz-PhilRice station, and Dapdap village (Tarlac). At all sites and in all years, tropical aerobic rice variety "Apo" (PSBRc-9) was direct dry seeded. At all sites, the row spacings were 25, 30, and 35 cm. At San Ildefonso and

Dapdap, 5 fertilizer N rates were used, whereas at Munoz-PhilRice, one rate in 5 different splits was used (Table 6.2.4). The San Ildefonso and Dapdap experiments were done in the wet seasons of 2004 and 2005, whereas the Munoz-PhilRice experiment was done in the wet season of 2004 and the dry season of 2005. In the wet seasons, no irrigation was applied, whereas in the dry season of 2005 at Munoz-PhilRice, crops received flush irrigation twice a week (on average). The soil type at San Ildefonso and Munoz-PhilRice is given above (water x N experiment description). The soil at Dapdap was a loamy sand with 78% sand, 17% silt, and 5% clay.

Table 6.2.4. N application rates and split distributions (kg ha^{-1}) at San Ildefonso, Dapdap, and Munoz-PhilRice in 2004 and 2005.

N-Treatment	Basal	10-14 DAE Early vegetative	30-35 DAE Mid-tillering	45-50 DAE Panicle Initiation	60 DAE Flowering	Total (kg ha^{-1})
San Ildefonso, Dapdap: N-amount x row spacing						
N_0	0	0	0	0	0	0
N_{60}	0	18	24	18	0	60
N_{90}	0	27	36	27	0	90
N_{120}	0	36	48	36	0	120
N_{150}	0	45	60	45	0	150
Munoz-PhilRice: N-split x row spacing						
NS_1	0	30	30	30	10	100
NS_2	0	20	50	30	0	100
NS_3	0	20	30	50	0	100
NS_4	23	23	29	25	0	100
NS_5	18	0	29	43	10	100

In *Laos*, we had a field experiment in 2006 on N,P,K fertilizer at two typical rainfed upland sites (Houay Khot and Somsanouk), using 9 different rice cultivars and 3 fertilizer treatments (Table 6.2.5, Table 6.2.6). No more site information was available.

Table 6.2.5. Rice cultivars grown under three fertilizer regimes, Laos, 2006.

Cultivar name	Type
Makhinsoung	Glutinous
Nok	Glutinous
Non	Glutinous
Laboun	Glutinous
Chao Do	Non glutinous
Apo	Non glutinous
B6144-MR-6-0-0	Non glutinous
Palawan	Non glutinous
IR60080-46	Non glutinous

Table 6.2.6. N,P,K fertilizer application rates, Laos, 2006

Treatment no	NPK Fertilizer kg ha^{-1}
1	0, 0, 0
2	50, 0, 0
3	50, 30, 30
4	30, 30, 30

6.2.3. Results China water

First, we present the results with respect to irrigation experimentation, Table 6.2.7. The experiments in 2001-2002 were discussed by Yang Xiaoguang et al. (2005) and Bouman et al. (2006); the experiments in 2003-2004 are analyzed by Xue et al. (submitted, 2007), and those in 2005-2007 by Limeng Zhang et al (in prep 2008). Here, we only present major highlights. At Changping (2001-2004), with the sandy soil and deep groundwater table, soil water tensions varied between 10 kPa (field capacity) to beyond 90-100 kPa which was the upper limit of the tension meters (Figures 6.2.1a-c). The highest amount of water applied (irrigation plus rainfall) was 769 mm in W0 in 2001, and the lowest was 469 mm in W4 in 2002. At Shangzhuang (2005-2006), the soil water tensions were much lower than at Changping because of the shallower groundwater table that fluctuated between 0.2 and 1.2 m both years. In 2005, soil water tensions had peak values of 30-50 kPa whereas in 2006 they stayed below 20 kPa (Figure 6.2.2). The highest amount of water applied was 668 mm in W1 in 2005, and the lowest was 450 mm in W3 in 2006.

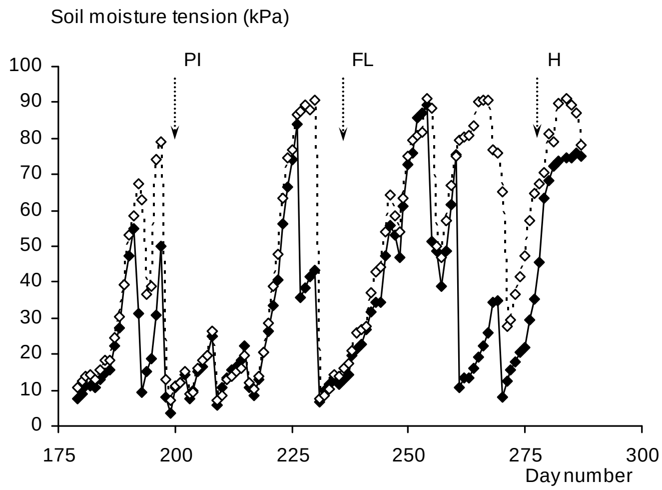


Figure 6.2.1a. Soil water tension in treatments W1 ( ) and W3 ( ) at 15-20 cm depth in 2001. Phenological developments are indicated PI (panicle initiation) and FL(flowering).

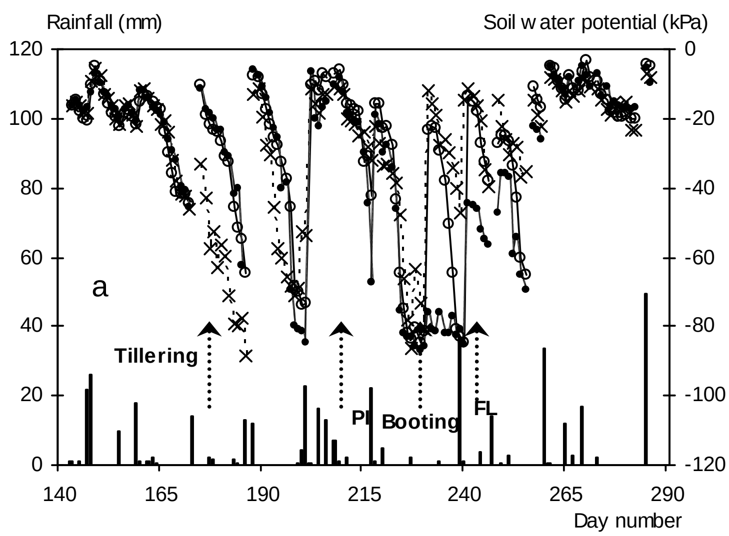


Figure 6.2.1b. Soil water potential in treatments W1 ( ), W2 ( ) and W3 ( ) at 15-20 cm depth in 2003. Daily rainfall is shown by black solid bars. Phenological developments are indicated by arrows: tillering, PI (panicle initiation), booting, FL(flowering).

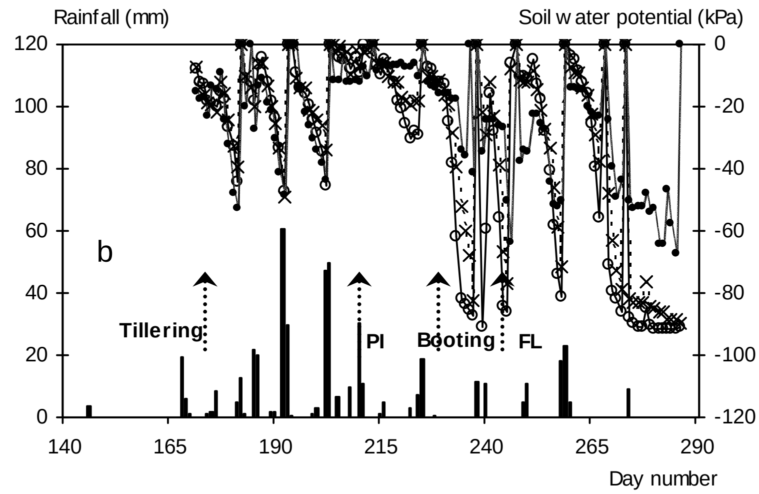


Figure 6.2.1c. Soil water potential in treatments W1 ( ), W2 ( ) and W3 ( ) at 15-20 cm depth and 2004. Daily rainfall is shown by black solid bars. Phenological developments are indicated by arrows: tillering, PI (panicle initiation), booting, FL(flowering).

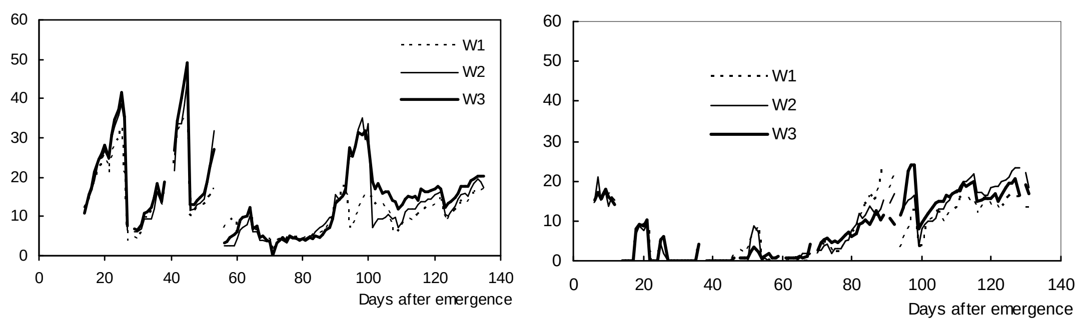


Figure 6.2.2. Soil water tension in treatments W1, W2, and w3 in 2005 (left panel) and 2006 (right panel) versus days after emergence.

Table 6.2.7. Amounts of water inputs by irrigation plus rainfall (mm) per water treatments at Changping, 2001-2004 and Shangzhuang, 2005-2006.

Treatment	2001	2002	2003	2004	2005	2006
W0	644	769				
W1	577	708	688	705	668	550
W2	586	620	618	675	526	490
W3	519	695	648	645	484	450
W4	469	547	578	605		

Our yield levels (Table 6.2.8) compare well with other reports for aerobic rice HD297 in northern China. At another site close to Beijing, Tao et al. (2006) reported yields of 5.7-6.1 t ha^{-1} with irrigation applied when the soil water tension at 15 cm depth exceeded 15 kPa, resulting in around 1400 mm total water input. In field experiments near Kaifeng (34°82'N, 114°51'E; 69 m asl), Feng et al. (2007) obtained relatively lower yields of 2.4-3.6 t ha^{-1} with 750-1000 mm total water input. In the same area, however, Bouman et al. (2007) reported farmers' yields of HD297 up to 5.5 t ha^{-1} with sometimes even as little as 566 mm total water input but with groundwater depth varying between 20 and 200 cm.

In our experiments, highest yields of 5.3-5.6 t ha^{-1} were obtained at Changping, despite the drier soil conditions there, while the yields at Shangzhuang (with wetter soil conditions) were not higher than 5.1 t ha^{-1} (Table 6.2.8). Even with low amounts of total water input, yields were still higher than 2.5 t ha^{-1} in all years except in 2003 where yield declined to 0.5 t ha^{-1} in W4. The low yields in 2003 were mainly caused by very low grain filling realized in all treatments, but especially so in W3 and W4 (Table 6.2.9). Around the time of flowering, from 77 to 97 days after emergence (DAE), less than 10 mm rainfall was recorded, with only 40 mm irrigation applied in W1 and W2, and no irrigation in W3 and W4. As a consequence, soil water tensions went up to above 100 kPa (data outside tensiometer measurement range). Rice is very sensitive to drought around flowering which leads to increased spikelet sterility and decreased grain filling (Cruz and O'Toole, 1984; Ekanayake et al., 1989). In the other years, soil water tensions at flowering were not as high as in 2003, and percentages of grain filling and yields were higher (Bouman et al., 2006).

Table 6.2.8. Yield of HD297 (averaged over N levels) (t ha^{-1}) for 5 water treatments at Changping, 2001-2004 and Shangzhuang, 2005-2006.

Treatment	2001	2002	2003	2004	2005	2006
W0	4.7	5.3				
W1	4.3	4.7	4.4	<u>5.6</u>	5.1	4.4
W2	4.2	3.9	3.4	5.4	4.7	4.3
W3	3.4	4.6	1.4	5.4	4.7	4.1
W4	2.5	3.0	<u>0.5</u>	5.0		

Table 6.2.9. Percentage grain filling (%) in the 2002-2004 field experiments at Changping, per irrigation treatment and fertilizer-N treatment.

Year	N amount (kg ha^{-1})	Water treatment				
		W0	W1	W2	W3	W4
2002	none	65	67	58	66	52
2003	0		70	68	30	12
	113		60	62	26	
	150		57	64	26	
	225/3splits		52	56	20	8
	225/5splits		53	59	12	10
2004	0		84	86	85	83
	75		83	82	82	81
	125		83	80	83	79
	175		81	77	84	80
	225		82	83	80	80

The trends in water productivity followed mainly the trends in yield since differences among amounts of water inputs were smaller than differences among yield (Table 6.2.10). Highest values were 0.88-0.95 kg grain m^{-3} water across both sites, whereas the lowest values were obtained at Changping in 2003 with the low percentages grain filling (see above). The water productivities are higher than the most common values of 0.3-0.4 kg grain m^{-3} water obtained in lowland rice (Tuong et al., 2005).

Table 6.2.10. Water productivity with respect to irrigation plus rainfall of HD297 at the highest N level (WP_{IR}, kg grain m^{-3} water) for 5 water treatments at Changping, 2001-2004 and Shangzhuang, 2005-2006.

Treatment	2001	2002	2003	2004	2005	2006
W0	0.73	0.58				
W1	0.75	0.61	0.70	0.84	0.75	0.66
W2	0.71	0.63	0.60	0.84	0.88	0.72
W3	0.65	0.67	0.25	0.88	<u>0.95</u>	0.73
W4	0.54	0.54	<u>0.10</u>	0.88		

On average across 2001-2004 at Changping, the computed evapotranspiration in the 'wettest' irrigation treatment was 596 mm (Table 6.2.11; which is 5.2 mm d^{-1}). Using the average amounts of rainfall in three typical years (Table 6.2.12), the calculated net irrigation requirements are listed in Table 6.2.13.

Table 6.2.11. Average calculated evapotranspiration (ET, mm) per growth stage, Changping 2001-2004.

Growth Stage	Evapotranspiration (mm)
Emergence-PI	286
PI-Booting	64
Booting-Flowering	91
Flowering-Maturity	155
Whole season	596

Table 6.2.12. Average rainfall (mm) per growth stage for three types of years, calculated from 50 years of weather data at Changping.

	Sowing-Emergence	Emergence-PI	PI-Booting	Booting-Flowering	Flowering-Maturity	Whole season
Wet (25%)	10	315	190	50	95	625
Average (50%)	4	245	130	30	85	510
Dry (75%)	0	145	85	25	45	335

Table 6.2.13. Net irrigation requirements calculated as evapotranspiration minus rainfall(mm) per growth stage for three types of years, calculated from 50 years of weather data at Changping.

	Sowing-Emergence	Emergence-PI	PI-Booting	Booting-Flowering	Flowering-Maturity	Whole season
Wet (25%)	66	0	0	39	62	167
Average (50%)	72	44	0	58	72	246
Dry (75%)	76	144	0	63	112	395

6.2.4. Results China water x nitrogen

Final aboveground biomass and grain yield for all experiments with water x nitrogen interaction are given in Table 6.2.14 for Changping (2003-2004), and in Table 6.2.15 for Shanzhuang (2005-2006). At Changping, irrigation had a significant effect on yield in all three experiments. Yields were highest in W1 and consistently declined through W2 to W3 and W4, though not all differences among treatments were significant. The application of any amount of fertilizer N either reduced yield and biomass (2003) or kept yield and biomass at the same level as without N fertilization (2004). In experiment 1, the application of N decreased yield but the difference with 0 N was not significant. In experiment 2, the application of N also decreased yield, but the difference between 0 N and 225 kg N ha^{-1} was significant only with three splits of the fertilizer. The interaction between irrigation and N was significant in experiment 2 but not in experiment 1. Like with biomass, splitting the fertilizer N in three gave significantly lower yield in W1 (and a bit in W4) but higher yield in W2 and W3 than splitting it in five. In experiment 3, the differences among N levels were small and inconsistent. Although the highest yield was obtained with 75 kg N ha^{-1}, significant difference only occurred between 75 and 225 kg N ha^{-1} levels.

Table 6.2.14. Total aboveground biomass and grain yield of aerobic rice for different irrigation and N treatments at Changping, Beijing, 2003-2004

Experiment	N rate (kg ha^{-1})	Biomass (t ha^{-1})					Grain yield (t ha-1)				
		W1	W2	W3	W4	Mean	W1	W2	W3	W4	Mean
	0	17.4	18.0	15.7	-	17.0	4.46	4.06	2.38	-	3.63
	113	18.3	16.4	14.0	-	16.2	3.91	3.68	2.50	-	3.36
	150	16.2	13.7	14.3	-	14.7	4.39	3.35	1.44	-	3.06
2003, Exp1	Mean	17.3	16.0	14.7	-	16.0	4.25	3.70	2.11	-	3.35
	W	1.54[a]					1.00				
	N	2.26					N/S				
	W*N	N/S[b]					N/S				
	0	14.7	11.2	16.2	13.2	13.8	3.27	2.60	1.58	0.60	2.01
	225/3splits	13.8	12.3	11.7	11.5	12.3	2.44	2.67	1.42	0.25	1.70
	225/5splits	15.8	11.9	10.6	13.3	12.9	3.61	2.36	0.77	0.53	1.82
2003, Exp2	Mean	14.8	11.8	12.8	12.7	13.0	3.11	2.54	1.26	0.46	1.84
	W	1.27					0.48				
	N	1.11					0.24				
	W*N	2.05					0.58				
	0	14.7	14.6	14.4	14.7	14.6	5.58	5.37	5.38	5.07	5.35
	75	16.5	17.8	17.3	14.9	16.6	6.03	5.70	5.29	5.50	5.63
	125	17.7	12.0	19.1	14.9	15.9	5.37	5.34	5.64	5.04	5.35
	175	17.0	17.2	15.7	13.6	15.9	5.41	4.78	5.39	4.73	5.08
2004, Exp3	225	16.5	17.5	14.3	18.2	16.6	5.53	5.57	5.06	4.61	5.19
	Mean	16.5	15.8	16.2	15.2	15.9	5.58	5.35	5.35	4.99	5.32
	W	N/S					0.25				
	N	N/S					0.39				
	W*N	N/S					N/S				

[a] LSD at P = 0.05; N/S means there was no significant difference at P = 0.05

At Shangzhuang, the only significant effect was by water (no significant effects of nitrogen, year, or interaction of year x water x nitrogen), Table 6.2.15. Yields were higher in W1 than in W3 in all cases. The addition of fertilizer-N reduced yields from the 0-N controls in 3 out of the 4 W x N combinations. In 2005, we noticed severe lodging of the crop at flowering, and the degree of lodging seemed to increase with increasing N application rate.

Table 6.2.15. Total aboveground biomass and grain yield of aerobic rice for different irrigation and N treatments at Shangzhuang, Beijing, 2005-2006.

Year	Irrigation treatment	Fertilizer Nitrogen treatment	Biomass (t ha^{-1})	Yield (t ha^{-1})
2005	W1	N0 (0 kg N ha^{-1})	15.0	5.3
		N2 (150 kg N ha^{-1})	14.0	4.5
	W3	N0	11.5	5.0
		N2	12.1	4.3
2006	W1	N0	9.3	5.0
		N2	10.7	4.7
	W3	N0	10.1	4.6
		N2	9.8	4.3
Source of variation		Year	**	Ns
		Water	Ns	*
		Nitrogen	Ns	Ns
		Water x nitrogen	Ns	Ns
		Year x water x nitrogen	Ns	Ns

Pr>F; <0.001:***; <0.01:**; <0.05:*; n.s.: not signification.

The lack of positive response of yield and crop growth parameters to N fertilization in all our experiments (coupled with a "luxurious N uptake", data not shown here, see Xue et al., submitted), indicates a high level of indigenous N supply (native soil N supply, N in irrigation water, atmospheric N deposition). A high level of soil N supply may have been the result of continuous over fertilization of the maize and wheat crops that preceded our experiments for the last 5-10 years. Around Beijing, the average N application rates in farmers' fields are 309 kg N ha^{-1} in winter wheat and 256 kg N ha^{-1} in maize (Zhao et al., 1997). Ma (1999) reported average combined N application rates of more than 500 kg N ha^{-1} in wheat-maize cropping systems in nearby Shandong Province. Such high levels of N application have resulted in increased soil N contents (Liu et al., 2003). Additionally, about 40 kg atmospheric N ha^{-1} is deposition annually in the Beijing area which contributes to indigenous soil N (Liu et al., 2006).

6.2.5. Results China NPK

Rainfall in the aerobic rice season was 1098 mm in 2005 and 629 mm in 2006. The irrigation inputs were estimated as 180 mm in 2005, and 240 mm in 2006. Because of heavy rainfall in 2005, the groundwater level increased from around 2 m depth to 0-0.8 m during the whole aerobic rice crop in 2005 (Figure 6.2.3). Consequently, the soil was very wet and the soil water tension at 15-20 cm depth remained within 0-15 kPa (Figure 6.2.4). In 2006, with less rainfall, the groundwater fluctuated around 0.6 m depth during July-August, but was about 1.8 m for the rest of the season. From mid August onward, the soil water tension ranged between 20 and 100 kPa.

Figure 6.2.3. Groundwater depth in during the aerobic rice crop, at Shuanghu, 2005 and 2006.

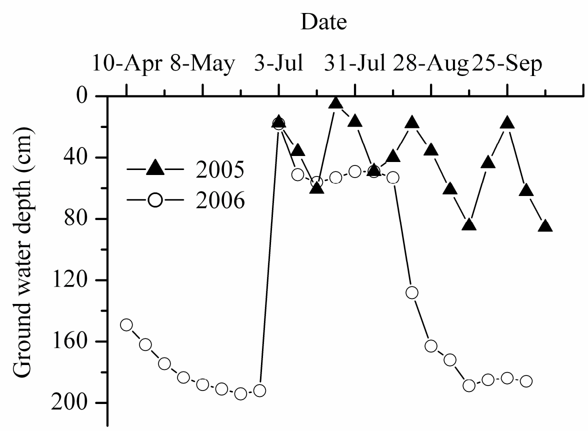
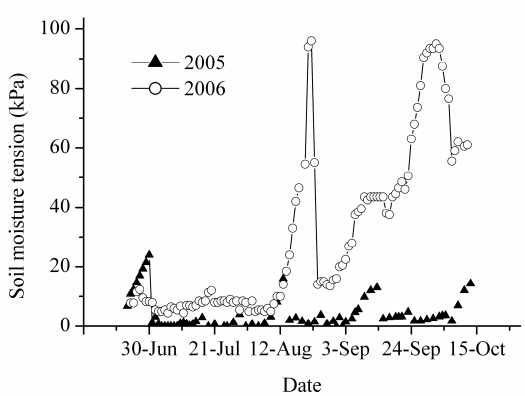


Figure 6.2.4. Soil moisture tension at 15-20-cm depth during the aerobic rice crop, at Shuanghu, 2005 and 2006.



Fertilizer applications significantly affected the aboveground biomass and grain yields of aerobic rice and winter wheat (Table 6.2.16). Aboveground biomass of aerobic rice ranged from 7.0 to 9.7 t ha^{-1} in 2005 and from 6.3 to 9.0 t ha^{-1} in 2006. For winter wheat, biomass yield ranged from 5.4 to 13.6 t ha^{-1} in AR-WW, and from 10.0 to 14.9 t ha^{-1} in WW-AR. The reduction in biomass was mainly the consequence of N omission. A cumulative N omission in winter wheat following aerobic rice caused a more severe reduction in biomass (6-7 t ha^{-1}) than in winter wheat preceding aerobic rice (4-5 t ha^{-1}).

Yields of aerobic rice varied from 3.2 to 4.1 t ha^{-1} in 2005 and from 2.9 to 4.0 t ha^{-1} in 2006, and of winter wheat from 2.7 to 7.1 t ha^{-1} in AR-WW and from 4.3 to 6.6 t ha^{-1} in WW-AR. Again, the yield loss due to cumulative N omission was much bigger in the wheat crop following aerobic rice. The losses in yield due to N omission were larger in winter wheat than in aerobic rice, indicating that the N demand of wheat was higher than that of aerobic rice, and that it could not be met from indigenous N supply.

The aboveground biomass and yield of aerobic rice and winter wheat were significantly reduced in the PK treatment (N omission) compared with the full NPK treatment. The reduction in grain yield was 0.5 (14%) and 0.8 t ha^{-1} (21%) for aerobic rice, in 2005 and 2006 respectively, and 2.3 (35%) and 4.3 t ha^{-1} (61%) for winter wheat in the subsequent years. There was no significant difference in either aboveground biomass or yield among NPK, NK (P omission) and NP (K omission) treatments in aerobic rice. P and K omissions caused significant reductions in yield of wheat in the AR-WW sequence: in the P and K omission treatments, the yield loss was 1.6 (23%) and 1.2 t ha^{-1} (17%).

Table 6.2.16. Aboveground biomass and grain yield of aerobic rice (AR) and winter wheat (WW) for two AR-WW (June 2005 to June 2006) and WW-AR (October 2005 to October 2006) cropping sequences.

Treatment	Aerobic rice		Winter wheat	
	Biomass (t ha^{-1})	Yield (t ha^{-1})	Biomass (t ha^{-1})	Yield (t ha^{-1})
AR-WW				
NPK	9.7 a	3.7 a	13.6 a	7.1 a
PK	7.3 b	3.2 b	6.7 c	2.8 c
NK	9.6 a	4.1 a	11.5 b	5.5 b
NP	9.6 a	4.1 a	12.7 ab	5.9 b
CK	7.0 b	3.3 b	5.4 c	2.7 c
WW-AR				
NPK	9.0 a	3.8 a	14.9 a	6.6 a
PK	6.5 b	3.0 b	10.3 bc	4.3 b
NK	8.1 a	3.7 a	13.1 ab	6.1 a
NP	8.8 a	4.0 a	13.7 a	6.4 a
CK	6.3 b	2.9 b	10.0 c	4.4 b

For each cropping sequence, different letters within a column indicate significant differences at $P<0.05$.

6.2.6. Results India water

At the WTC-IARI station in 2005, the amount of irrigation plus effective rainfall was 1314 mm in I0, 1014 mm in I20, and 894 mm in I40. In 2006, these amounts were 100 mm in I0, 980 mm in I20, and 780 mm in I40. Compared with typical amounts of water applied to lowland rice fields (under alternate wetting and drying), these amounts translate into water savings of the order of 30-40% for production levels of 4 t ha^{-1}. The soil water tensions in all three irrigation treatments slightly exceeded the intended target on a few occasions but were mostly within the intended ranges (Figure 6.2.5). Yields were highest in I0 and significantly decreased for most varieties with decreasing amount of irrigation water in I20 and I40 (Figures 6.2.6a,b). Water productivity with respect to irrigation plus rainfall of Pusa Rice Hybrid 10, Pusa 834, IR74371-46-1-1, IR55423-01 (Apo1) and Proagro 6111 was about 0.42-0.47 kg m^{-3} at I20 irrigation, while it was 0.50 kg m^{-3} at I40 irrigation (Figure 6.2.7).

Figure 6.2.5. Soil water tension (kPa) measured at different depths in treatments I0, I20, and I40 in the variety screening trial at WTC-IARI station, Delhi, 2005.

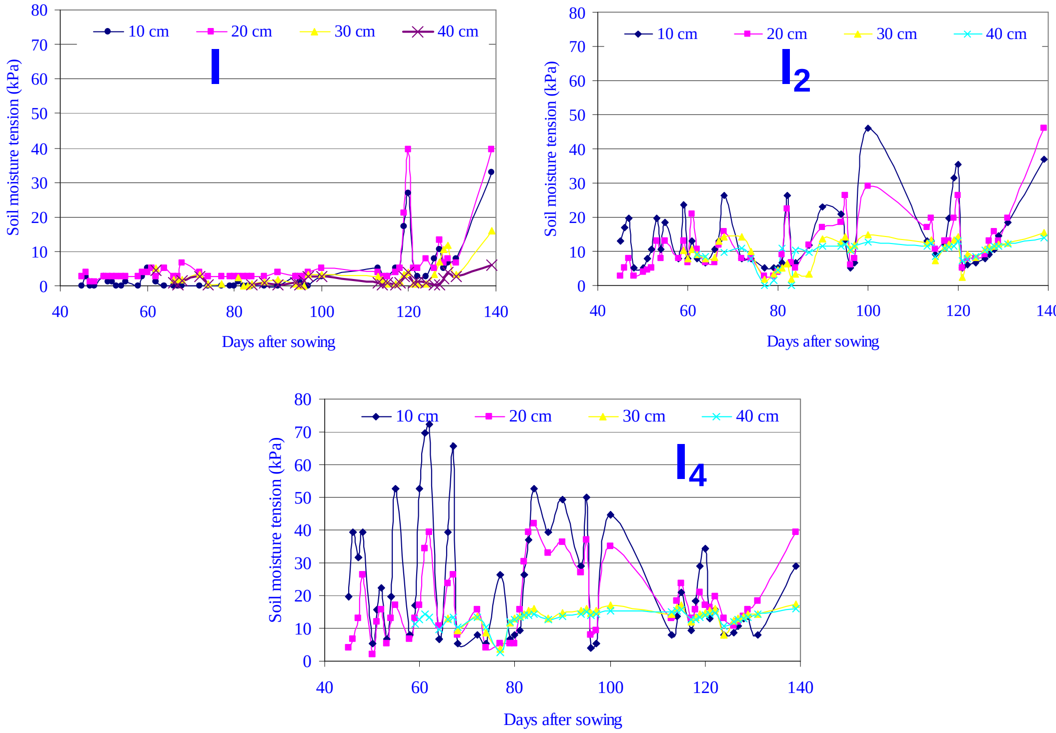


Figure 6.2.6a. Yield of different genotypes under aerobic soil conditions at three irrigation levels at the WTC-IARI station, Delhi, 2005.

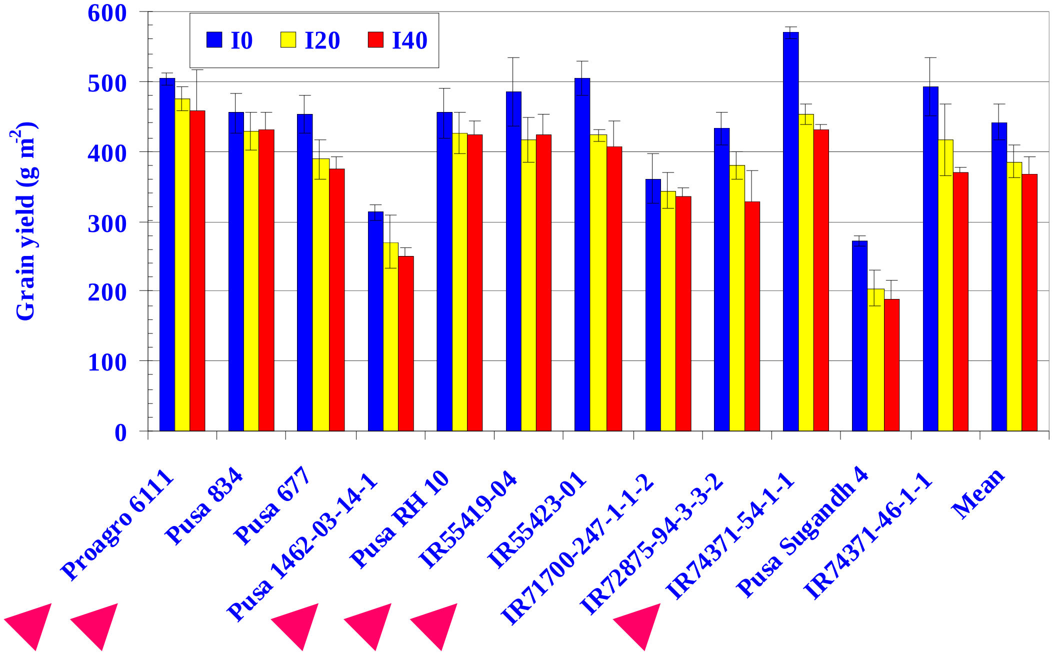


Figure 6.2.6b. Yield of different genotypes under aerobic soil conditions at three irrigation levels at the WTC-IARI station, Delhi, 2006.

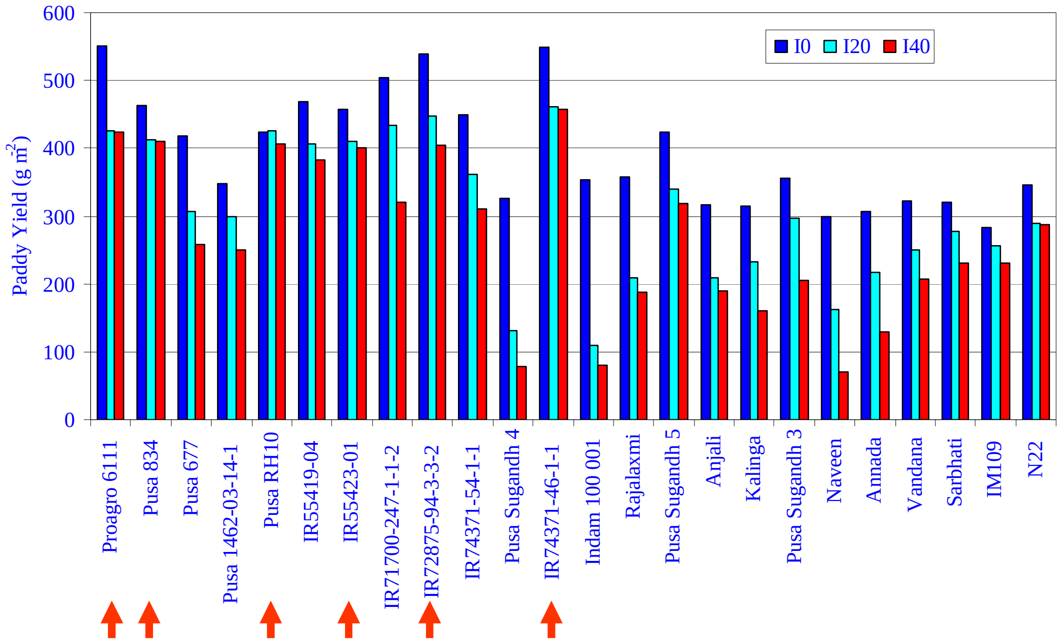
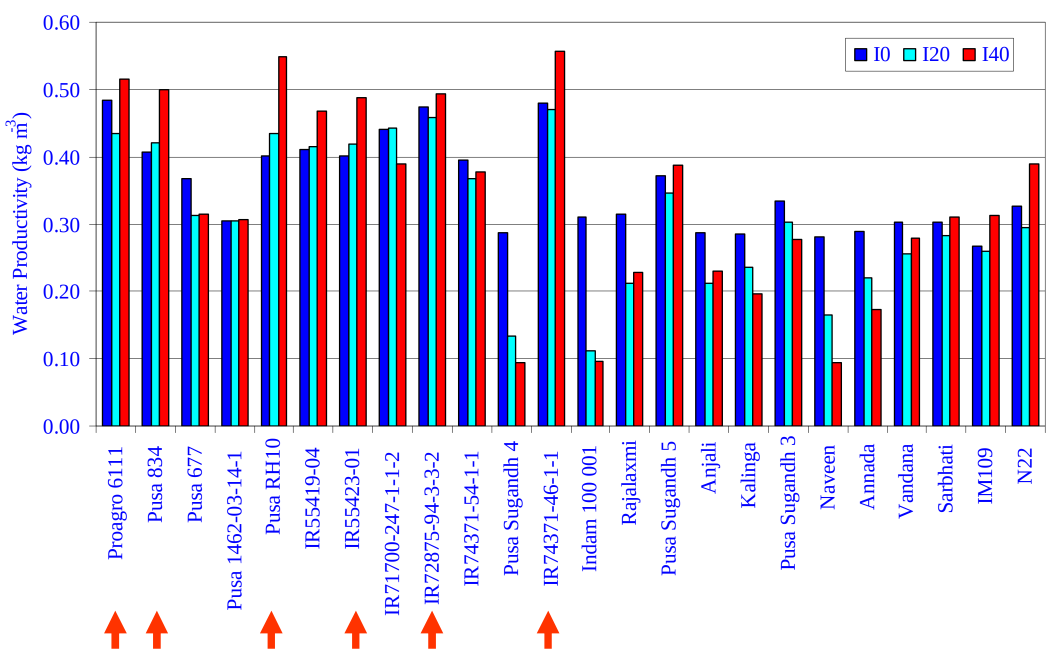


Figure 6.2.7. Water productivity with respect to irrigation plus effective rainfall (kg m^{-3}) of different genotypes under aerobic soil conditions at three irrigation levels at the WTC-IARI station, Delhi, 2006.



6.2.7. Results Philippines water x nitrogen

The amount of water put in by irrigation in W1 was higher in the Philippines than in China (Table 6.2.17). Using surface irrigation, the lowest amount of irrigation water used was 480 mm in San Ildefonso, and the highest was 1070 mm in Munoz-PhilRice (with 22 to 200 mm rainfall). Using sprinkler irrigation in Munoz-CLSU, the amount of combined irrigation and rain water varied from as little as 274 mm to as much as 1300 mm.

Table 6.2.17. Irrigation water input (mm) per water treatment, rainfall during the experiment (mm), and fertilizer-N inputs per nitrogen treatment (kg ha^{-1}), at Munoz (PhilRice) and san Ildefonso (BASC/BSWM), 2005-2007 dry seasons.

Site	Year	W1	W2	W3	Rain	N1	N2	N3	N4
Munoz (PhilRice)	2005	1070	630	590	22	0	60	120	165
Munoz (PhilRice)	2006	1040	680	560	200	0	60	120	165
Munoz (CLSU)	2006	681	418	378	Included	0	60	120	165
Munoz (CLSU)	2007	1300	280	274	Included	0	60	120	165
San Ildefonso	2006	900	540	480	105	0	60	120	165
San Ildefonso	2007	970	610	510	230	0	60	120	165

The soil was much wetter in the Philippine experiments than in the China experiments, as evidenced by the much lower soil moisture tensions (Figures 6.2.8a-d). Despite that the fields were never flooded, the soil water tensions stayed mostly within 0-10 kPa for all treatments at Munoz-PhilRice in 2005, within 0-20 kPa at Munoz-PhilRice in 2006, within 0-20 kPa at San Ildefonso in 2006, and within 0-30 kPa at San Ildefonso in 2007 (no tensiometer data at Munoz-CLSU). The lack of clear differences in soil water tension among irrigation treatments, and the relatively low levels of soil water tension were caused by the development of perched groundwater tables underneath the experiments (Figures 6.2.9a-c). At Munoz-PhilRice in 2005, the groundwater depth as measured tubes installed in bunds surrounding the experiment fluctuated between 1.5 and 2 m, but the groundwater measured in tubes installed within the experimental fields fluctuated between 0 and 0.5 m depth. At San Ildefonso, in 2007, the "real" groundwater depth varied around 2 m, but underneath the experimental field, it fluctuated between 0 and 0.7 m depth.

Figure 6.2.8a. Soil water tension (kPa) at 15-35 cm depth in water x N trial, Munoz (PhilRice), dry season 2005.

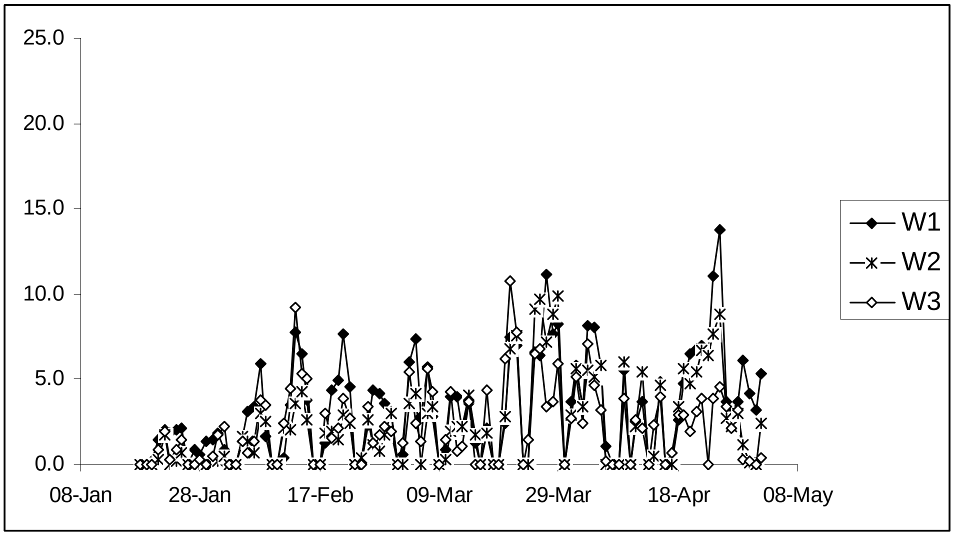


Figure 6.2.8b. Soil water tension (kPa) at 15-35 cm depth in water x N trial, Munoz (PhilRice), dry season 2006.

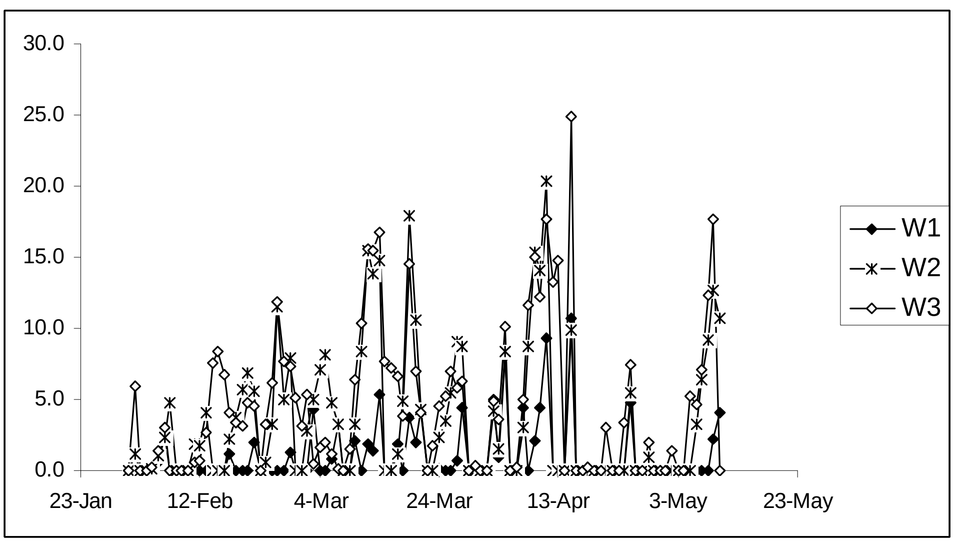


Figure 6.2.8c. Soil water tension (kPa) at 15-35 cm depth in water x N trial, San Ildefonso, dry season 2006.

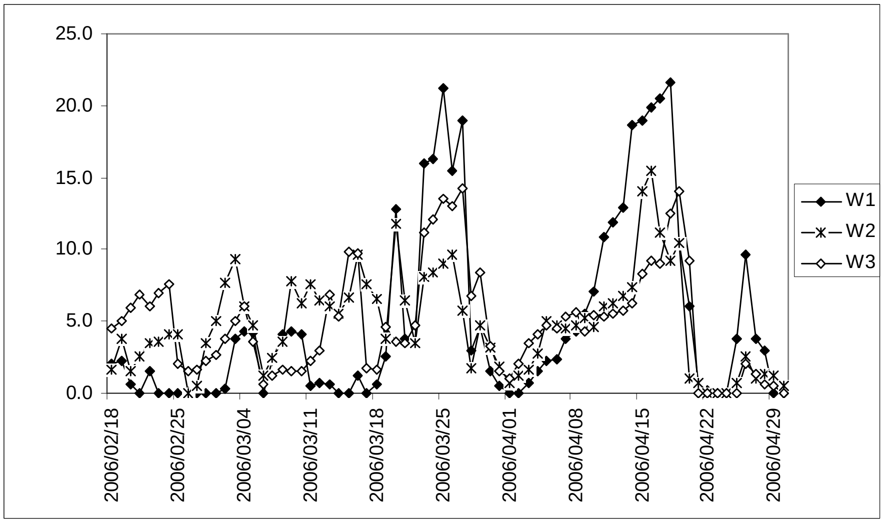


Figure 6.2.8d. Soil water tension (kPa) at 15-35 cm depth in water x N trial, San Ildefonso, dry season 2007.

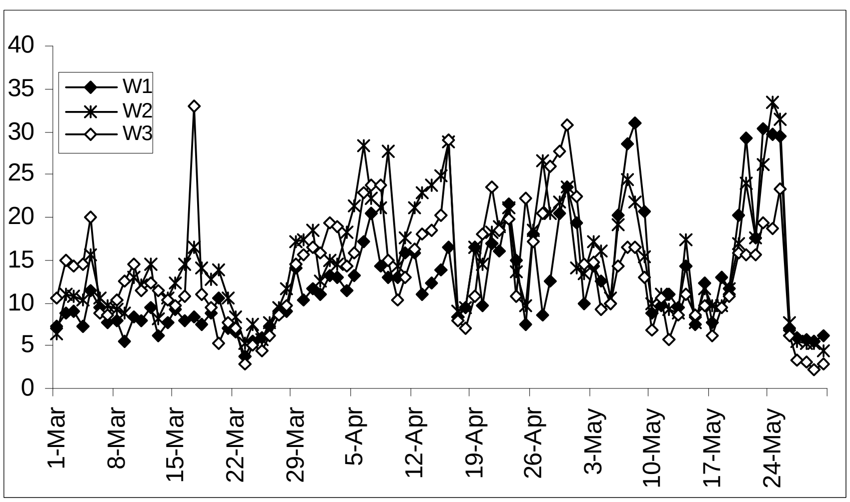


Figure 6.2.9a. Groundwater depth (cm) measured at three locations in water x N trial, Munoz (PhilRice), dry season 2005.

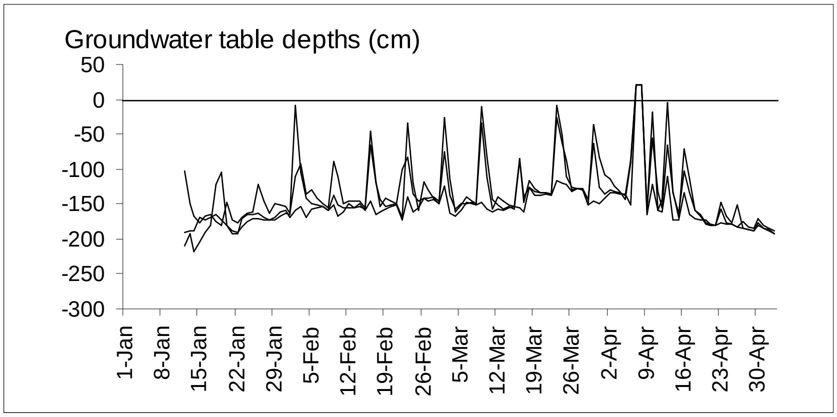


Figure 6.2.9b. Perched groundwater table depth (cm) measured at three locations in water x N trial, Munoz (PhilRice), dry season 2005.

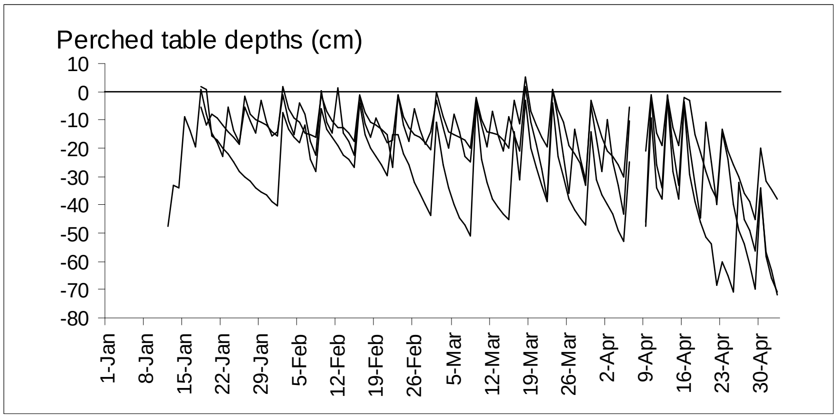
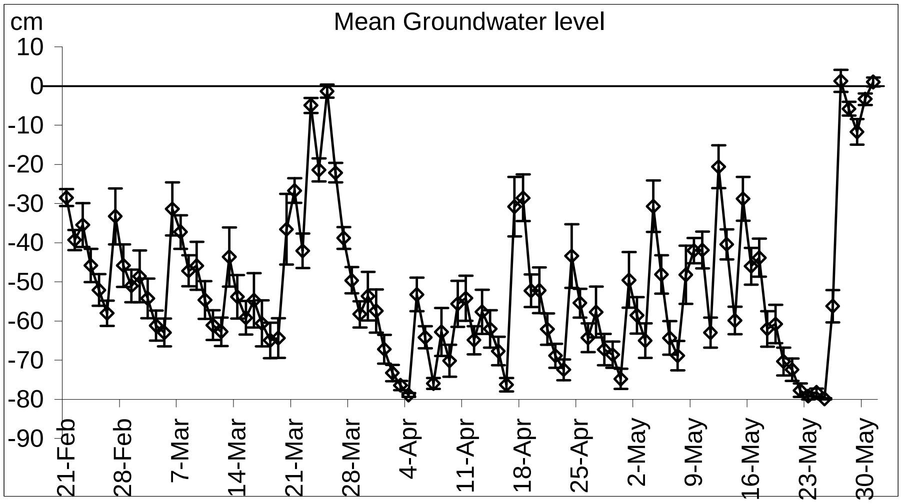


Figure 6.2.9c. Perched groundwater table depth in water x N trial, San Ildefonso, dry season 2007.



Highest yields were 5.4 t ha^{-1} in Munoz-PhilRice 2005, 2.9 t ha^{-1} in Munoz-PhilRice 2006, 3.4 t ha^{-1} in Munoz-CLSU 2006, 3.8 t ha^{-1} in Munoz-CLSU 2007, 3.1 t ha^{-1} in San Ildefonso 2006, and 3.5 t ha^{-1} in San Ildefonso 2007 (Tables 6.2.18a-f). The yields were a bit lower in Munoz-CLSU with sprinkler irrigation. Because of the absence of differences in soil water tensions among treatments, there were no significant effects of irrigation water regime in most experiments. Only in Munoz-CLSU was yield much higher in W1 than in W2 and W3, in both 2006 and 2007, though across all water treatments, the effect of water was not significant. The effect of N was significant at the 1% or 5% level in all experiments: yields increased with increasing N application rate, especially in Munoz (both sites). At San Ildefonso, the yield increase with added N was smaller than at Munoz.

Table 6.2.18a. Yield (t ha^{-1}) of Apo in water x N trial, Munoz (PhilRice), dry season 2005.

Mean	W1	W2	W3	Ave
N1	1.39	1.24	1.41	1.35
N2	3.15	2.73	2.54	2.81
N3	4.00	4.50	4.54	4.34
N4	5.02	5.43	5.25	5.23
Ave	3.39	3.47	3.43	

Effect of N is significant at the 1% level; effect of water is not significant.

Table 6.2.18b. Yield (t ha^{-1}) of Apo in water x N trial, Munoz (PhilRice), dry season 2006.

Mean	W1	W2	W3	Ave
N1	0.78	0.90	0.88	0.85
N2	1.47	1.30	1.14	1.30
N3	2.61	2.61	2.31	2.51
N4	2.92	2.68	2.26	2.62
Ave	1.94	1.87	1.65	

Effect of N is significant at the 5% level; effect of water is not significant.

Table 6.2.18c. Yield (t ha^{-1}) of Apo in water x N trial, Munoz (CLSU), dry season 2006.

Mean	W1	W2	W3	Ave
N1	1.67	1.89	1.27	1.61
N2	2.26	2.02	1.67	1.98
N3	2.60	1.63	2.31	2.18
N4	3.43	2.04	2.25	2.57
Ave	2.49	1.89	1.88	

Effect of N is significant at the 5% level; effect of water is not significant

Table 6.2.18d. Yield (t ha^{-1}) of Apo in water x N trial, Munoz (CLSU), dry season 2007.

Mean	W1	W2	W3	Ave
N1	2.25	1.98	1.24	1.82
N2	3.52	2.08	1.79	2.46
N3	3.77	2.21	2.01	2.66
N4	3.56	2.16	1.83	2.52
Ave	3.28	2.10	1.72	

Effect of N and water is significant at the 5% level.

Table 6.2.18e. Yield (t ha^{-1}) of Apo in water x N trial, San Ildefonso, dry season 2006.

Mean	W1	W2	W3	Ave
N1	2.41	2.11	2.48	2.33
N2	2.31	2.65	2.58	2.51
N3	2.97	2.79	2.69	2.82
N4	2.77	3.03	3.09	2.96
Ave	2.61	2.65	2.71	

Effect of N is significant at the 5% level; effect of water is not significant.

Table 6.2.18f. Yield (t ha^{-1}) of Apo in water x N trial, San Ildefonso, dry season 2007.

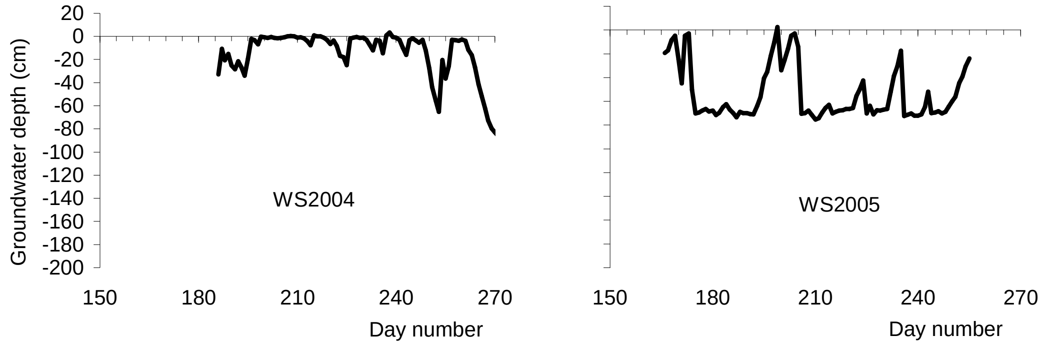
Mean	W1	W2	W3	Ave
N1	2.34	2.53	3.05	2.64
N2	3.25	3.61	3.25	3.37
N3	3.38	3.45	3.05	3.30
N4	3.78	2.99	3.54	3.44
Ave	3.19	3.15	3.22	

Effect of N and water are significant at the 1% level.

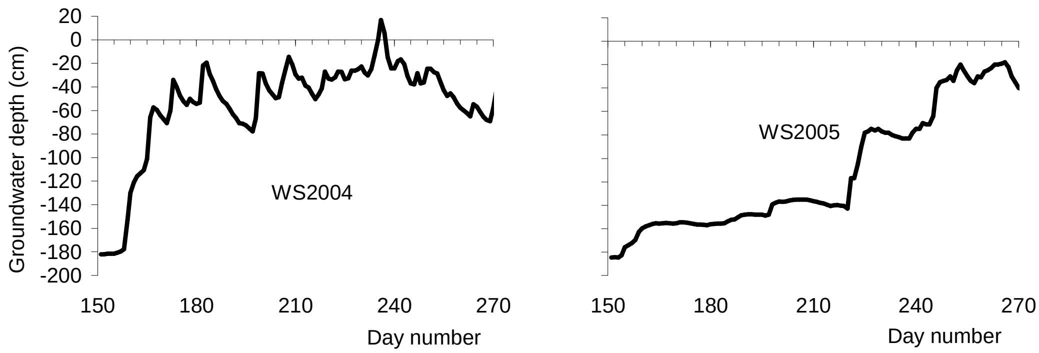
6.2.8. Results Philippines nitrogen x row spacing

Here, we present the results only with respect to N application rate and distribution (there is no effect of row spacing: see paragraph "Crop establishment" for analysis). More detailed results are presented by Lampayan et al. (in prep). Total seasonal rainfall was 1210 mm in 2004 and 911 mm in 2005 at San Ildefonso, 984 mm in 2004 and 897 mm in 2005 at Dapdap, and 1492 mm in 244 and 20 mm in 2005 (dry season!) at Munoz-PhilRice. Groundwater depths are given in Figure 6.2.10. Groundwater tables were relatively deep at Munoz-PhilRice, at 1-1.8 m. Groundwater tables were relatively shallow in 2004 in San Ildefonso and Dapdap where they reached into the root zone. Except for Dapdap in 2005, soil water tensions measured in the root zone usually varied between 0 and 15 kPa only (Figure 6.2.11). At Dapdap in 2005, soil water tensions went up to 35-40 kPa.

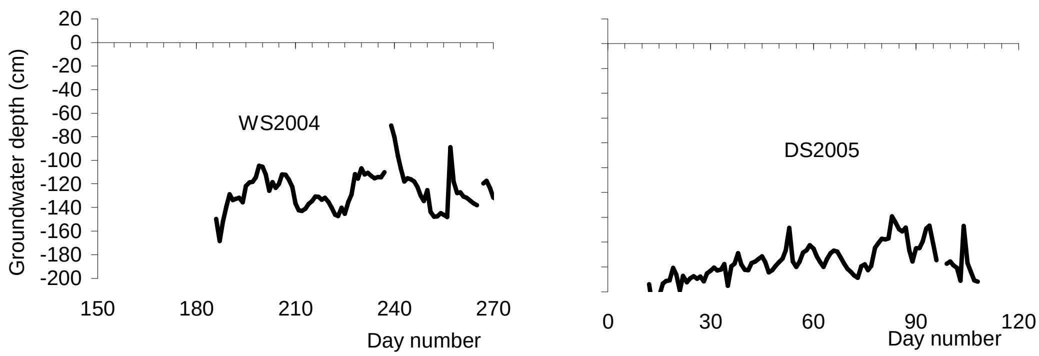
Figure 6.2.10. Groundwater depth (cm) in the N x row spacing experiments in San Ildefonso (Bulacan), Dapdap, and Munoz-PhilRice, in 2004-2005.



(a) Bulacan

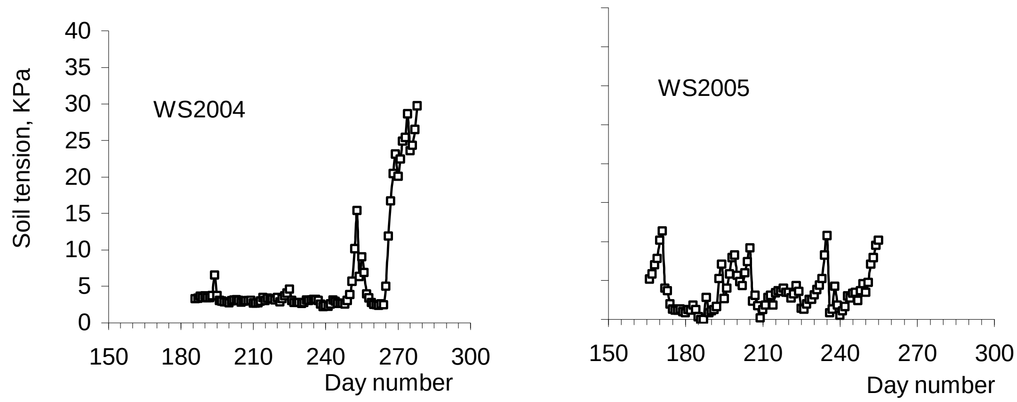


(b) Dapdap

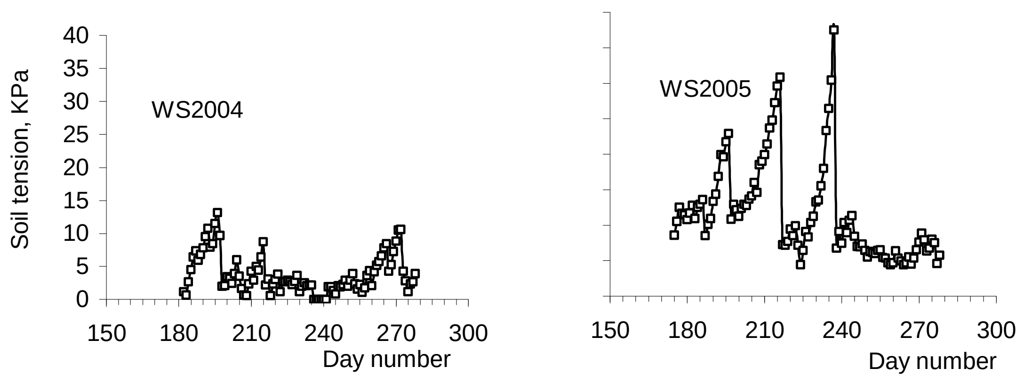


(c) PhilRice

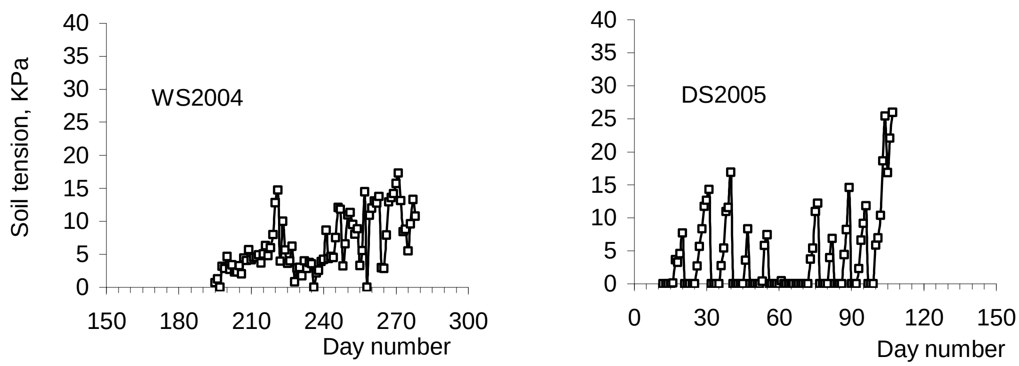
Figure 6.2.11. Soil water tension (kPa) at 10-15 cm depth in the N x row spacing experiments in San Ildefonso (Bulacan), Dapdap, and Munoz-PhilRice, in 2004-2005.



(a) San Ildefonso



(b) Dapdap



(c) PhilRice

In the N rate experiment, maximum yields in the different sites and years were 4-4.5 t ha^{-1} (Table 6.2.19). Fertilizer N addition had a significant positive effect on yield. At San Ildefonso, highest yields were obtained at 60-120 kg N ha^{-1} (statistically the same), and in Dapdap at 120-150 kg N ha^{-1} (statistically the same). Except in San Ildefonso in 2005, there was considerable lodging in the 120 and 150 kg N ha^{-1} treatments (Table 6.2.20), and we can speculate that yields would have been higher without lodging.

Table 6.2.19. Yeld and total biomass (averaged over row spacings) of Apo in different N application treatments at San Ildefonso and Dapdap, 2004 and 2005 wet seasons.

Site and year	N treatment	Yield (t ha^{-1})	Total biomass at harvest (t ha^{-1})
San Ildefonso, 2004	N_0	2.18 a	5.52 a
	N_{60}	4.13 b	12.94 b
	N_{90}	4.64 b	16.22 c
	N_{120}	4.04 b	15.23 c
	N_{150}	3.62 b	15.11 c
San Ildefonso, 2005	N_0	2.52 a	6.70 a
	N_{60}	3.77 b	9.79 b
	N_{90}	4.11 c	10.35 bc
	N_{120}	4.28 c	10.22 bc
	N_{150}	4.28 c	11.48 c
Dapdap, 2004	N_0	1.69 a	4.65 a
	N_{60}	3.31 b	9.28 b
	N_{90}	3.98 c	11.19 c
	N_{120}	4.48 d	11.84 cd
	N_{150}	4.85 d	12.46 d
Dapdap, 2005	N_0	1.67 a	3.86 a
	N_{60}	3.07 b	6.93 b
	N_{90}	3.35 bc	6.88 b
	N_{120}	3.77 cd	8.42 c
	N_{150}	4.00 d	9.27 c

Means followed by a different letter (within columns) are significantly different at the 5% level.

Table 6.2.20. Degree of lodging (%) of Apo at San Ildefonso and Dapdap, 2004 and 2005 wet seasons.

N treatment	Site and year			
	San Ildefonso WS2004	San Ildefonso WS2005	Dapdap WS2004	Dapdap WS2005
N_0	0 a	0 a	0 a	0 a
N_{60}	3 a	0 a	0 a	2 a
N_{90}	42 b	0 a	8 a	4 a
N_{120}	56 bc	0 a	46 b	44 b
N_{150}	62 cd	0 a	76 c	67 b

Means followed by a different letter (within columns) are significantly different at the 5% level.

In the N splitting experiment, yields were 2-3.9 t ha^{-1} in the wet season and 5.4-6.1 t ha^{-1} in the dry season (Table 6.2.21). There was hardly any significant effect of N splitting on yield, except that the treatments with a late application of 10 kg N ha^{-1} at flowering (NS_1 and NS_5) produced significantly higher yields in 3 out of the 4 cases.

Table 6.2.21. Grain yield and total biomass (averaged over row spacings) of Apo in different N split treatments at Munoz-PhilRice, 2004 wet season and 2005 dry season. N treatments are explained in the Method section above.

Year	N treatment	Yield (t ha^{-1})	Total biomass at harvest (t ha^{-1})
2004	NS_1	3.90 b	10.0 a
	NS_2	3.48 a	9.6 a
	NS_3	3.46 a	9.5 a
	NS_4	3.24 a	9.6 a
	NS_5	3.36 a	9.1 a
2005	NS_1	6.10 b	12.1 b
	NS_2	5.80 ab	11.6 ab
	NS_3	5.69 ab	11.6 ab
	NS_4	5.40 a	10.8 a
	NS_5	6.10 b	11.6 ab

Means followed by a different letter (within columns) are significantly different at the 5% level.

6.2.9. Results Laos NPK

Results of the variety x nutrient trials are given in Table 6.2.22 and Table 6.2.23. Significant differences in grain yield were observed among rice cultivars at the two sites. No significant differences in grain yield were observed among fertilizer treatments at the two sites. However, yields were consistently highest in the 50-30-30 NPK treatment for all cultivars at Houy Khot, while they were consistently highest in the 50-0-0 NPK treatment at Somsanouk. Finally, grain yield was, on the average, higher at Somsanouk (fallowed for four years) than at Houy Khot (continuously cropped to upland rice for the last three years).

Table 6.2.22. Grain yield (t ha^{-1}) for different cultivars under 4 nutrient treatments, Houay Khot, 2006.

	Fertilizer treatment kg (N-P-K) ha^{-1}			
Variety	0-0-0	50-0-0	50-30-30	30-30-30
Makhinsoung	0.97	1.38	1.91	1.04
Nok	0.84	1.21	1.86	1.55
Non	2.18	2.06	2.65	2.21
Laboun	1.66	1.72	2.00	1.83
Chaodor	1.27	1.09	1.34	1.24
Apo	2.50	2.57	3.11	2.48
B6144-MR-6-0-0	2.14	2.42	3.11	2.71
Palawan	0.94	1.03	1.54	1.40
IR60080-6A	1.87	2.07	3.19	2.67

Table 6.2.23. Grain yield (t ha^{-1}) for different cultivars under 4 nutrient treatments, Somsanouk, 2006.

	Fertilizer treatment kg (N-P-K) / ha			
Variety	0-0-0	50-0-0	50-30-30	30-30-30
Makhinsoung	3.49	4.65	4.31	3.83
Nok	3.72	3.95	3.82	4.02
Non	4.42	4.01	4.00	4.08
Laboun	3.39	3.99	3.96	3.88
Chaodor	3.02	3.43	3.21	2.71
Apo	5.07	4.75	3.95	4.90
B6144-MR-6-0-0	3.95	4.44	3.84	4.13
Palawan	3.94	3.94	3.31	3.94
IR60080-6A	3.94	4.15	3.78	3.94

6.2.10. Conclusion

China. In Beijing, the highest aerobic rice yields of HD297 were 5-5.6 t ha-1 with 600-700 mm total irrigation plus rainfall water (and in Shangzhuang 2005-2007, with any unaccounted capillary rise). Yields were 2.5-4.3 t ha-1 with 450-550 mm water input. Very low yields (down to 0.5 t ha^{-1}) were obtained with dry soil (water tension higher than 100 kPa) around flowering. The main reason for the low yields was the high spikelet sterility. Irrigation is essential at flowering time if there is no rain. The average seasonal evapotranspiration (ET) requirement was about 600 mm. With shallow groundwater, capillary rise can meet most of the ET and there may be no need to irrigate. With deep groundwater tables, the net irrigation needs are 167 mm in a typical 'wet rainfall year" (2 times irrigation), 246 mm in a typical "average rainfall year" (3 times irrigation), and 395 mm in a typical "dry rainfall year" (4-5 times)

In Beijing, the application of any amount of fertilizer N either reduced yield and biomass (2003, 2005, 2006 experiments) or kept yield and biomass at the same level as without N fertilization (2004 experiments). Fields in northern China cropped to summer maize and/or winter wheat may have been over fertilized for many years to the extent that they are now 'saturated' with N. Moreover, they may receive large amounts of N through atmospheric deposition (around 40 kg atmospheric N ha^{-1} in the Beijing area). To assist farmers with fertilizer N management in aerobic rice, an inventory is needed of indigenous soil N supply in the target area. In case of consistent historic ove rfertilization, a paradigm shift in N management research is needed from optimizing fertilizer N supply to managing N-saturated soils.

Nitrogen omission in aerobic rice-wheat and wheat-aerobic rice cropping systems in Mencheng County caused a marked decline in aboveground biomass and grain yield of both aerobic rice and winter wheat, whereas P and K omission had less effect. The relatively strong yield reduction in the absence of fertilizer N indicates that, at this site, the native soil N supply is inadequate to meet crop requirements. Conversely, the low response to P and K omissions of aerobic rice in the first crop cycle may indicate a relatively adequate native soil P and K supply. However, P and K became yield limiting for winter wheat in both the first and the second cycle, because of a higher demand for nutrients by winter wheat than aerobic rice. Calculated for the whole system, grain yield decreased by 44%, 11% and 7% in the AR-WW sequence, and by 30%, 6% and 0% in the WW- AR sequence due to N, P and K omission.

India. The genotypes Pusa Rice Hybrid 10, Proagro6111 (hybrid), Pusa834 and IR55423-01 (Apo) produced a yield of more than 4 t ha^{-1} under aerobic production system irrigated at 40 kPa soil water tension in the root zone. Among the yield components, biomass, number of grains m^{-2}, and number of grains ear^{-1} were most affected by increasing soil water tensions (data not shown). Compared with typical amounts of water applied to lowland rice fields (under alternate wetting and drying), the amounts applied in the aerobic rice experiments of 780-1324 mm (irrigation plus effective rainfall) translated into water savings of the order of 30-40% for production levels of 4-4.5 t ha^{-1}. Compared with China, yields in the India experiments were lower and the soil wetter as evidenced by the lower soil water tension (0-40 kPa). The fertilizer application rates in the experiments were 150 kg N ha^{-1}, 60 kg P ha^{-1}, and 40 kg K ha^{-1}. Further research is needed to find out if yields can be increased by changing fertilizer management.

Philippines dry season. Except for two experiments at Munoz-PhilRice in 2005with maximum yields of 5.4-6.1 t ha^{-1}, maximum yields of variety Apo were in the range of 2.9-3.8 t ha^{-1}. These yields are much lower than the yields in China while the soil water tensions in the root zone were much lower (usually in the 0-30 kPa range), indicating much wetter soil conditions. There was hardly any effect of irrigation water application rate because shallow perched water tables (reaching up and into the root zone) developed underneath the aerobic rice fields. Most of the experiments were conducted in typical lowland rice environments with relatively shallow groundwater tables and poor internal drainage of the soils. Therefore, high yields were realized with as little as 274-590 mm irrigation water input (with groundwater providing a lot of the required water to keep soil water tensions within the 0-30 kPa range and to meet crop evaporative demand). Yield responded positively to fertilizer N applications in all experiments, with an application of 120 kg ha^{-1} sufficient to reach maximum yields.

Philippines wet season.. Like in the dry season experiments, soil water tensions in the root zone were generally low, between 0-15 kPa, because of heavy rainfall in the wet season and shallow groundwater tables. Maximum yields were, with 3.9-4.5 t ha^{-1}, usually higher in the wet season than in the dry season (see above). Fertilizer N addition had a significant positive effect on yield. At San Ildefonso, highest yields were obtained at 60 kg N ha^{-1} and above (statistically the same), and in Dapdap at 120 kg N ha^{-1} and above (statistically the same). Overall, there was considerable lodging in the 120 and 150 kg N ha^{-1} treatments. Heavy winds and strong rains frequently occur in the Philippines (central Luzon) near the end of the rainy season, and the risk of lodging needs to be addressed in fertilizer N recommendations. In the two seasons at Munoz-PhilRice, a late application of 10 kg N ha^{-1} at flowering produced significantly higher yields. Otherwise, yield was insensitive to distribution of N during the growing season.

Laos. The few results for Laos (1 year, 2 sites) show the variability in nutrient response among sites. The same cultivars produced yields of 3-5.1 t ha^{-1} at one site (Somsanouk) and only 0.8-3.2 t ha^{-1} at the other site (Houay Khot). More years of experimentation are needed to derive firm nutrient management recommendations.

6.2.10.1. Simulation modeling

We used the crop growth simulation model ORYZA2000 (Bouman et al., 2001) to extrapolate experimental findings to wider environments (soil, weather, hydrology) and compute irrigation water requirements and yield levels under different irrigation management scenarios. Two studies were done in China (Table 6.2.24); one extrapolating experimental data from Kaifeng, and one extrapolating experimental data from Beijing to soils of the Yellow River Basin. The Kaifeng study was reported by Feng et al. (2007) and Bouman et al. (2007). Here, a summary of the simulation study using the Beijing data is presented, adapted from Xue et al. (submitted to Irrigation Science).

Table 6.2.24. Sites of modeling activities per country

Activity/ Country	Phil	China	India	Laos	Thai
Simulation modeling		Beijing -> Yellow River Basin, Kaifeng			

6.2.11. Method

First, the experimental data collected near Beijing in 2002-2004 (see "Water and nutrient dynamics" paragraph) were used to parameterize and evaluate the ORYZA2000 model. The evaluated variables included total aboveground biomass, biomass of crop organs, leaf area index, grain yield, and soil water tension. Next, ORYZA2000 was used to simulate the yield, water inputs (by irrigation and rainfall), and evapotranspiration (ET) of HD297 under nine irrigation regimes, on five soil types, and for 34 years of historical weather data. ET flows are real water losses that deplete water from the system (Molden et al., 2003), whereas total water inputs satisfy the ET needs plus any deep percolation losses and additions to the soil water storage. The irrigation regimes were zero irrigation, and 75 mm irrigation water applied when the soil water tension at 20 cm depth reached 10, 20, 30, 50, 70, 100, 200, and 500 kPa. Two soils were from our experiment fields in 2002 and 2003, which were named Exp02 and Exp03, respectively. The other three soils were a typical silty loam, loam, and sandy loam, with water retention properties taken from Wopereis et al (1996). These five soils represent typical soils of the Yellow River Basin (YRB) (Zi, 1999).

6.2.12. Results

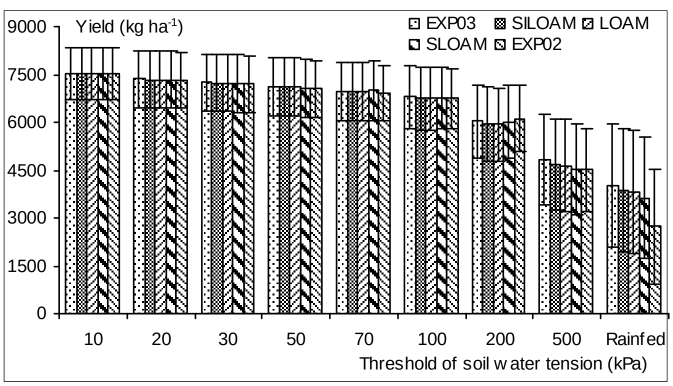
Figure 6.2.12 gives the results of the simulations for different soils and irrigation regimes. Yields were quite comparable on all soils and only gradually declined from an average of around 7500 kg ha^{-1} with soil water content kept around field capacity, to 6750 kg ha^{-1} with irrigation applied at 100 kPa soil water tension. Standard deviations caused by differences in weather were about 900 kg ha^{-1}. With irrigation applied at thresholds above 100 kPa, yields decreased faster and started to vary among the soils. Yields decreased with decreasing water-holding capacity of the soils, from Exp03 to silt loam, loam, sandy loam, and Exp02. Under completely rainfed conditions, average yields still ranged from about 2700 kg ha^{-1} on the poorest soil to 4000 kg ha-$^{-1}$ on the best soil. As the year-to-year variability in rainfall was not mitigated by irrigation, the standard deviation went up to some 1900 kg ha^{-1}.

The long-term average rainfall was 477 mm (Figure 6.2.12b, rainfed bar). Irrigation water inputs varied most among soil types at relatively low thresholds of irrigation application, and decreased in reverse order of yield with soil type: from Exp02, to sandy loam, loam, silt loam, and Exp03. To keep the soil at field capacity (irrigation at 10 kPa) required daily irrigations and an average amount of irrigation water over all soils of 10485 mm. However, the amount of required irrigation water decreased fast with increasing threshold of soil water tension. At 20 kPa, irrigation water inputs were already reduced to 823 mm on Exp03 and to 1260 mm on Exp02. At 100 kPa, irrigation water inputs were as low as 200 mm on Exp03 and 320 mm on Exp03.

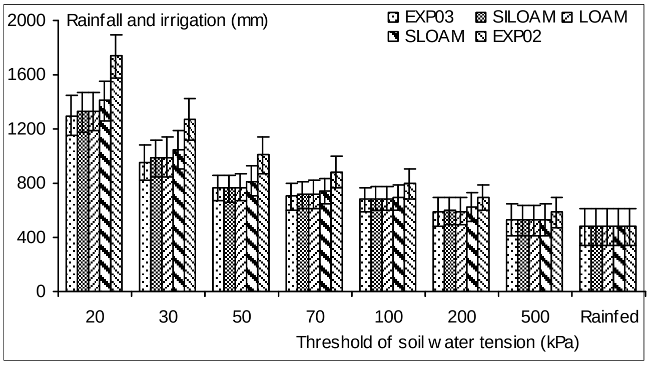
Differences in evapotranspiration (ET) among the soils were minimal with low irrigation thresholds, and slowly increased with increasing thresholds (Figure 6.2.12c). With a continuously wet top soil with irrigation applied at 10 kPa, total ET was relatively high at around 690 mm. ET dropped fast to around 510 mm with irrigation applied at 20 kPa to 370-416 mm under rainfed conditions.

Both water productivities WP_{IR} and WP_{ET} showed a maximum value with intermediate irrigation regimes. The WP_{IR} increased from as low as 0.07 g kg^{-1} at 10 kPa irrigation threshold to 0.89-1.05 g kg^{-1} at 200 kPa because the decrease in irrigation water requirements over that range outweighed the decrease in yield (Figure 6.2.12d). Beyond 200 kPa, however, the yield decrease outweighed the reduced irrigation water requirements, and WP_{IR} declined again to 0.55-0.82 g kg^{-1} under rainfed conditions. The differences in WP_{IR} among soil types were relatively pronounced, and showed the same trends as those in yield. The WP_{ET} was highest and stable at about 1.45 g kg^{-1} between irrigation thresholds of 20 to 100 kPa, and then declined gradually to 0.70-0.93 g kg^{-1} under rainfed conditions (Figure 6.2.12e).

Figure 6.2.12. Average simulation results over 34 years as a function of threshold level of soil water tension for irrigation on five soils: yield (a), rainfall plus irrigation (b), evapotranspiration (c), water productivity based on total water input WP_{IR} (d), water productivity based on evapotranspiration WP_{ET} (e). The error bars indicate the standard deviation caused by weather.

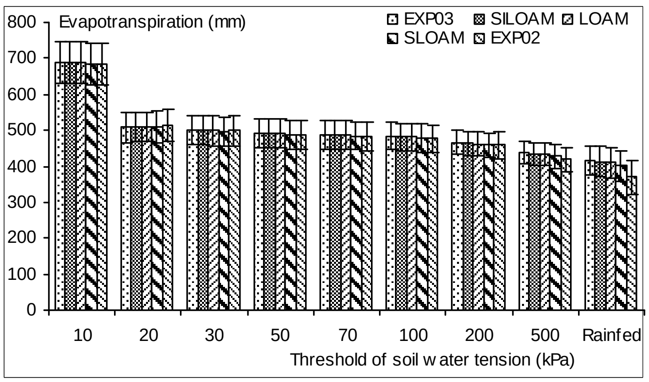


A



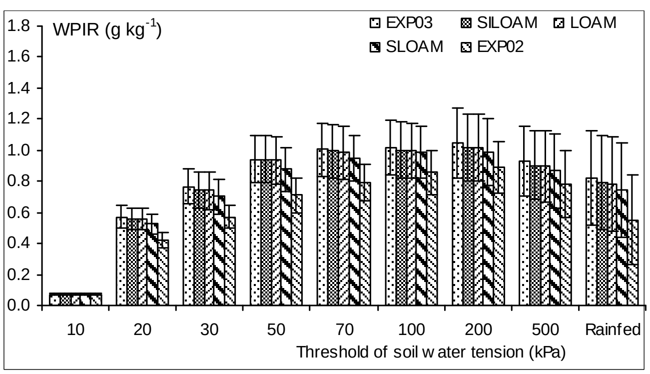
Rainfall and irrigation (mm)
EXP03
SILOAM
LOAM
SLOAM
EXP02
2000
1600
1200
800
400
0
20
30
50
70
100
200
500
Rainfed
Threshold of soil water tension (kPa)

B



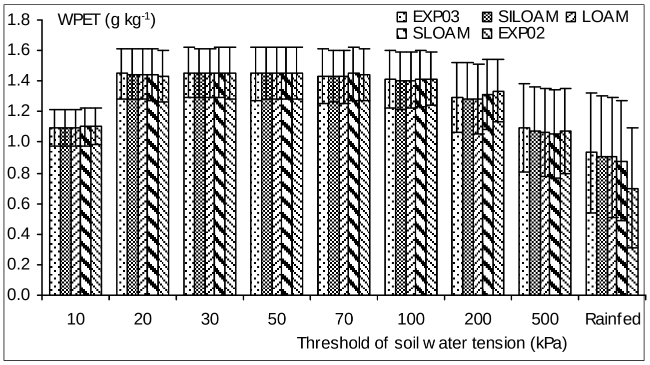
Evapotranspiration (mm)
EXP03
SILOAM
LOAM
SLOAM
EXP02
800
700
600
500
400
300
200
100
0
10
20
30
50
70
100
200
500
Rainfed
Threshold of soil water tension (kPa)

C



WPIR (g kg-1)
EXP03
SILOAM
LOAM
SLOAM
EXP02
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10
20
30
50
70
100
200
500
Rainfed
Threshold of soil water tension (kPa)

D



E

Average maximum simulated yields were 6.8-7.5 t ha^{-1} with soil water potentials in the root zone staying between 0 and 100 kPa. These yields were 0.8-1.5 t ha^{-1} higher than the maximum of 6 t ha^{-1} in our field experiments. There may be at least 3 reasons for this difference. First, in nearly all of the experimental treatments, there were periods when the tensiometers failed to record because the threshold of 100 kPa was exceeded, so that higher soil water tensions occurred that could have reduced yields. When simulated soil water tensions were allowed to reach 200 kPa, yields already dropped to 6-6.1 t ha^{-1} (Figure 6.2.12a). Second, aerobic rice is a relatively new crop and best management practices still need to be developed. Therefore, the management applied in the field experiments may not have resulted in the highest possible yields. Third, the variety HD297 might have been sink limited under high-yielding conditions. Analyzing yield formation in HD297, Bouman et al. (2006) reported that the source strength (quantified by light use efficiency) of this variety was comparable to that of lowland varieties with yield potentials of more than 8 t ha^{-1}. The panicle size of HD297, however, may be too small to attain such yields (visual observation by authors).

Simulated yields sharply decreased with irrigation water application above the 100 kPa soil water tension threshold. But even under completely rainfed conditions, yields were still 2.7-4 t ha^{-1}, depending on soil type. Required water inputs declined sharply with irrigation thresholds increasing from 10 to 50 kPa, and then declined slowly with increasing thresholds from 50 kPa onwards. Since yield followed the opposite trend with irrigation threshold, the water productivity WP_{IR} showed a maximum at intermediate irrigation thresholds (Figure 6.2.12d). When water resources are limited, the best irrigation scheme would optimize water productivity rather than grain yield. In our simulations, the highest WP_{IR} was obtained at irrigation thresholds of 100-200 kPa, with yields of 6-6.8 t ha^{-1} and only 112-320 mm irrigation water applied (and 477 mm rainfall). In farmers' practice such irrigation amounts would translate into 2-4 irrigation applications of 50-75 mm each, which is about the irrigation frequency of early adopters of aerobic rice in the Kaifeng area (Bouman et al., 2007). Compared with other upland crops in the YRB, this irrigation water requirement is lower than that for winter wheat (Sun et al., 2006) but higher than that for summer maize (Wang et al., 2001).

Evapotranspiration (ET) was quite stable over a wide range of irrigation thresholds, and only declined slightly from about 690 mm at 20 kPa to 370-416 mm under purely rainfed conditions. At 20 kPa, the total water inputs were 1300-1739 mm (depending on soil type), and hence some 610-1049 mm of water left the root zone by deep percolation. The amount of deep percolation gradually decreased to

61-107 mm under purely rainfed conditions. Although deep percolation is a loss to farmers, it re-enters the hydrological cycle and is potentially available for reuse, for example by groundwater pumping (Hafeez et al., 2007). Therefore, for irrigation system managers, the optimum irrigation scenario could be when the highest water productivity with respect to evapotranspiration is obtained (Loeve et al., 2004). In our simulations, highest levels of WP_{ET} were realized with irrigation thresholds between 10 and 100 kPa (Figure 6.2.12e). Irrigation thresholds of 100-200 kPa therefore seem a suitable balance between the interests of farmers (striving for high WP_{IR}) and irrigation system managers (striving for high WP_{ET}).

Soil type had relatively little effect on yield except under purely rainfed conditions, with the lighter-textured soil with lowest soil water holding capacity having lowest yields. Soil type had the strongest effect on irrigation water inputs with irrigation application thresholds below 70 kPa. The effect of soil type was most pronounced on water productivity with respect to total water inputs: WP_{IR} decreased on soils with decreasing water holding capacity.

6.2.13. Conclusion

Field experiments and simulations show that, on typical freely-draining soils of the YRB, aerobic rice yields with HD297 can reach up to 6 t ha^{-1}, with, on average some 477 mm rainfall and 112-320 mm of irrigation water dosed in 2-4 applications to keep the soil water tension in the root zone below 100-200 kPa. Drought around flowering should be avoided by targeted irrigation applications to avoid the risk of spikelet sterility that would result in low grain yields. To further increase yield and productivity of aerobic rice in the YRB, we suggest the following research activities:

1. “Management”. Optimizing the productivity of aerobic rice in a cropping system context. Studies should address the potential to increase yields through improved crop management practices such as establishment (such as optimum seed density, row spacing) and nutrient management (macro and micro nutrients). Moreover, such studies should look at the potential role of aerobic rice in multiple cropping systems and crop rotations (such as optimizing sowing dates, crop durations, cropping calendar), and should address whole cropping system productivity.

2. “Germplasm improvement”. The development of new varieties should focus on the potentials for yield increase through increasing the sink size and harvest index of the current variety HD297.

3. “Model improvement”. The current version of ORYZA2000 captures the effect of water stress at flowering through the effect of increased canopy temperature on spikelet sterility only (Bouman et al., 2001). More insight in the mechanisms of spikelet sterility should be obtained and built in ORYZA2000, especially at soil water tensions above 100 kPa. Also, ORYZA2000’s water balance model should be specifically tested in dry soil conditions where the soil water potential exceeds 100 kPa. The presented model scenarios used

weather data from Beijing and freely-draining soils only. Next steps would be to study the effect of groundwater tables on yield and water requirements, and to include weather data from other sites on the YRB.

6.3. Objective 3: Sustainability

Yield decline under continuous monocropping of upland rice has been reported in Japan, Brazil, and the Philippines (Nishizawa et al. 1971; Pinheiro et al, 2006; Ventura and Watanabe 1978; George et al. 2002). Yield decline of continuous upland rice is generally believed to be caused by soil sickness, which may include the buildup of nematodes (Nishizawa et al. 1971) or soil pathogens (Ventura et al. 1981), changes in nutrient availability in the soil (Lin et al. 2002), or growth inhibition by toxic substances from root residues (Nishio and Kusano 1975). So far, the causes of yield decline in continuous upland rice are still unknown, and we don’t know if the same yield decline will occur in continuous aerobic rice systems. Documenting any yield decline in continuous aerobic rice, and understanding its causes, is necessary to develop sustainable management strategies of aerobic rice systems. Here, we present our work done in the Philippines with pot and field experiments (Table 6.3.1).

Table 6.3.1. Sites of sustainability research activities per country

Activity/country	Philippines	China	India	Laos	Thailand
Field experiment	Los Banos, Dapdap				
Pot experiment	Los Banos				

6.3.1. Gradual yield decline

In 2001, IRRI established a long-term field experiment to compare the agronomic performance of aerobic and flooded rice. The field experiment was conducted at the International Rice Research Institute (IRRI) farm at Los Baños, Laguna, Philippines (14°11′N, 121°15′E, 21 m asl) in both dry season (DS, January-May) and wet season (WS, June-October). There were three main fields, subdivided into plots with different treatments, and four replications. Up to 2004, there were three water treatments in the main fields: aerobic rice in both DS and WS, flooded rice in both DS and WS, and aerobic in DS and flooded rice in WS. The continuous aerobic and flooded treatments were divided into a “full N” treatment and a “0-N treatment”. Full N was 150 kg urea-N ha^{-1} in the DS and 70 kg urea-N ha^{-1} in the WS. In all fields, phosphorus (60 kg P ha^{-1} as solophos), potassium (40 kg K ha^{-1} as potassium chloride), and zinc (5 kg Zn ha^{-1} as zinc sulfate heptahydrate) were incorporated one day before transplanting. From 2004 onward, changes were introduced to study effects of crop rotations, fallowing, and conversion of flooded fields into “fresh” aerobic fields. The continuous aerobic rice cropping continued till 2008. Variety “Apo” (PSBRc9) was used throughout the experiment. Flooded plots were puddled and kept continuously flooded with 5-10 cm of water depth from transplanting until 2 weeks before harvest. The aerobic plots were dry-ploughed and harrowed but not puddled during land preparation. One day before transplanting, aerobic plots were soaked with irrigation water overnight to facilitate transplanting. Transplanting was done for aerobic rice to keep seedling density constant across seasons. Afterward, aerobic plots were flash irrigated with about 5 cm water each time only when the soil moisture tension at 15 cm depth reached –30 kPa. Around flowering, the threshold for irrigation was reduced to –10 kPa to prevent spikelet sterility.

In our project, we summarized the results over the period 2001-2004 (1), initiated follow-up studies on understanding the causes of yield decline with a focus on nutrient supply (2), studied "restoration" attempts in the long-term field experiment by crop rotations (3), and continued monitoring yields under continuous aerobic conditions in the period 2005-2007 (4). In the next sections, we present results for each of these four activities.

Peng et al. (2006) and Bouman et al. (2005) presented the key findings of the long-term field experiment with respect to yield and water use. Here, we summarize the findings on yield decline and present some additional data on nematode counts. Aerobic rice yields were higher in the DS than in the WS (Figure 6.3.1). In the DS, yields were lower in 2003-2004 than in 2001-2002, though the difference was only small. In the WS, yields were 3.5-4 t ha-1 without any clear pattern over the years. When compared with the flooded yields, the yields under aerobic conditions declined consistently from 2001 to 2004, both the DS and in the WS. However, it is unclear whether this relative decline is a consequence of increasing flooded yields over time or decreasing aerobic yields over time.

In 2004, the flooded plots in the previous six seasons were converted to "fresh" aerobic plots, while flooded plots only in WS became flooded in 2004 DS. This change allowed a direct comparison between rice grown under aerobic conditions in the soil where flooded rice has been grown continuously in previous seasons (first season aerobic rice) and in the soil where aerobic rice has been grown continuously in previous six seasons (seventh season aerobic rice). Here, the effect of continuous cropping is very clear: the yield in the same year in the "fresh" aerobic field is some 2.5 t ha^{-1} higher than in the seventh-season continuous aerobic field, while the yield in the "fresh" aerobic field is only 1.5 t ha^{-1} less than in the flooded field (Table 6.3.2).

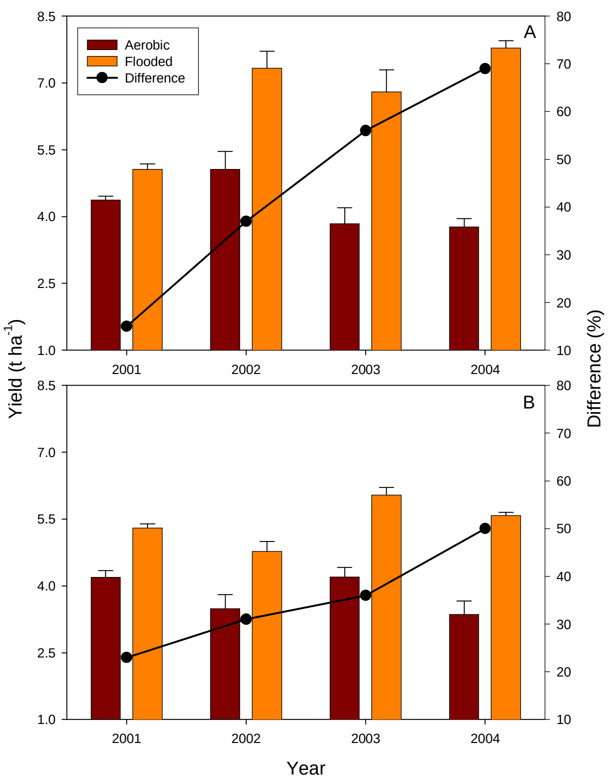
Table 6.3.2. Grain yield, total biomass, and harvest index of Apo grown under aerobic conditions in the soil where flooded rice has been grown continuously in previous seasons (1st season aerobic rice) or in the soil where aerobic rice has been grown continuously in previous six seasons (7th season aerobic rice) in comparison with flooded rice in the dry season of 2004 at IRRI farm.

Parameters	1st season aerobic rice (A_{1st})	7th season aerobic rice (A_{7th})	Flooded rice (F)
Grain yield (t ha^{-1})	6.32 b	3.77 c	7.78 a
Total biomass (g m^{-2})	1343 b	862 c	1604 a
Harvest index (%)	45.3 b	45.4 b	47.1 a

Within a row, means followed by different letter are significantly different at 0.05 probability level according to Least Significant Difference (LSD) test.

Figure 6.3.1. Grain yield of Apo grown under aerobic and flooded conditions and the yield difference between aerobic and flooded rice in dry seasons (A) and wet seasons (B) of 2001-04 at IRRI farm. The aerobic yields include all fields that were aerobic in both the aerobic-aerobic and the aerobic-flooded treatments. Source: Peng et al., 2006.

Fig. 1



We measured nematodes (*Meloidogyne graminicola*) in the roots of the stubbles within two weeks after harvest (Table 6.3.3). Before our experiment started, nematode numbers in the stubble of flooded rice (in all plots) of the previous experiment were 2-9 g^{-1} fresh root weight. In the continuous aerobic fields, the number of nematodes increased rapidly with a peak in the 2002 and 2003 DS. The aerobic-flooded treatment was not able to suppress nematodes in the aerobic phase whereas in the flooded phase, nematode counts were very low again. In the continuous flooded fields, nematode counts remained low except for the 2002 and 2003 DS where moderate levels were counted. Although nematode counts were clearly high in the aerobic fields, no statistical correlation was found between nematode count and yield level over time. Moreover, whereas the "fresh" aerobic field in the 2004 DS had a high yield of 6.3 t ha^{-1} and the seventh-season a low yield of 3.8 t ha^{-1}, the number of nematodes was higher in the fresh aerobic field (658) than in the seventh-season aerobic field (368), though because of high spatial variability these differences were not significant.

Table 6.3.3. Number of *Meloidogyne graminicola* nematodes per gram fresh root weight after harvest, in Apo grown under aerobic (A) and flooded (F) conditions, IRRI farm 2001-2004.

	Continuous aerobic	Alternate aerobic-flooded	Continuous flooded Aerobic in 2004 DS
Baseline flooded	6	9	2
	Aerobic DS Aerobic WS	Aerobic DS Flooded WS	Flooded DS Flooded WS
2001 DS	875 (A)	279 (A)	6 (F)
2001WS	491 (A)	11 (F)	4 (F)
2002 DS	2530 (A)	1760 (A)	134 (F)
2002 WS	1499 (A)	27 (F)	34 (F)
2003 DS	2089 (A)	3054 (A)	380 (F)
2003 WS	694 (A)	51 (F)	45 (F)
2004 DS	368 (A)	35 (F)	658 (A)

6.3.2. Yield restoration

From 2004 onward, restoration attempts were made by introducing periods of flooding, fallowing, and different crops into the long-term aerobic rice field experiment (Table 6.3.4).

1. Flooding: In 2004 DS and WS, the alternate aerobic-flooded fields (aerobic rice in DS and flooded rice in WS) were converted into flooded rice. In the 2005 DS, aerobic rice was planted again to create a 1^{st} season aerobic rice after three seasons of flooded rice. Full N rates were applied.

2. Fallowing: In 2004 DS and WS, half of the continuous aerobic rice fields were converted to fallow. In the 2005 DS, aerobic rice was planted again to create a 1^{st} season aerobic rice after two seasons of fallow. Full N rates were applied. The remaining half was kept continuously cropped to aerobic rice since 2001 DS.

3. Crop rotation: In 2004 the flooded fields from 2001-2003 were cropped to aerobic rice in both DS and WS. In 2005, they were reverted back to flooded rice to serve as reference for aerobic rice in other fields. In 2006, different upland crops were planted in the Ds and WS: soybean, maize, sweet potato. In addition, a fallow was included. After harvest, all above-ground material was removed from the plots. In 2007DS, aerobic rice was planted again. Full N rates were applied.

Table 6.3.4. Cropping pattern in long-term aerobic rice experiment at the IRRI farm, 2002-2007.

	Main field I		Main field II	Main field III			
2001 DS	Aerobic		Aerobic	Flooded			
2001WS	Aerobic		Flooded	Flooded			
2002 DS	Aerobic		Aerobic	Flooded			
2002 WS	Aerobic		Flooded	Flooded			
2003 DS	Aerobic		Aerobic	Flooded			
2003 WS	Aerobic		Flooded	Flooded			
2004 DS	Fallow	Aerobic	Flooded	Aerobic			
2004 WS	Fallow	Aerobic	Flooded	Aerobic			
2005 DS	Aerobic	Aerobic	Aerobic	Flooded			
2005 WS	Aerobic	Aerobic	Aerobic	Flooded			
2006 DS		Aerobic		Soy bean	Maize	Sweet potato	Fallow
2006 WS		Aerobic		Soy bean	Maize	Sweet potato	Fallow
2007 DS		Aerobic		Aerobic	Aerobic	Aerobic	Aerobic
2007 WS		Aerobic		Aerobic	Aerobic	Aerobic	Aerobic

The effect of fallowing and flooding on yield of aerobic rice is given in Table 6.3.5. In the N-fertilized fields, the effect of both two seasons fallowing and three season of flooding was significantly positive: yield increased by about 1.5 t ha^{-1} in the fist season and 1 t ha^{-1} in the second (relative to the long-term aerobic rice fields). There was no difference in yield between the fallowing and flooding restorations. In the 0-N fertilized fields, there was no significant effect of both the fallowing and the flooding restoration: yields were statistically the same as in the long-term aerobic rice fields.

Table 6.3.5. Effect of two seasons of fallow and three seasons of flooding on the yield of Apo in aerobic and flooded fields in 2005DS and 2005WS.

Treatment	Yield (t ha^{-1})	
	With N	Without N
2005 DS		
9th Aerobic	3.03 c	2.68 b
1st Aerobic after fallowing	4.43 b	2.50 b
1st Aerobic after flooding	4.51 b	2.89 b
Flooded	6.79 a	4.86 a
2005 WS		
10th Aerobic	3.18 c	2.57 c
2nd Aerobic after fallowing	4.27 b	3.02 b
2nd Aerobic after flooding	4.01 b	2.82 bc
Flooded	5.71 a	5.03 a

Within a column, means followed by different letter are significantly different at 0.05 probability level according to Least Significant Difference (LSD) test.

The effect of fallowing and different crop rotations on yield of aerobic rice is given in Table 6.3.6. In the first season, aerobic rice yields after the three upland crops were statistically the same, and about 0.8-1.1 t ha^{-1} higher than after fallowing. Compared with all the previous years, aerobic rice yields after upland crops were relatively high at 5.4-5.8 t ha^{-1}. Surprisingly, even the yield in the continuous aerobic rice fields was relatively high and comparable with the yields after the three upland crops (no statistical analysis done yet).

Table 6.3.6. Effect of two seasons of fallow and different upland crops on the yield of Apo in aerobic fields in 2007DS.

Treatment	Yield (kg ha^{-1})
2007 DS	
13th Aerobic (0-N)	3.02
13th Aerobic (full N)	5.19
1st Aerobic after fallowing	4.63 b
1st Aerobic after maize	5.41 a
1st Aerobic after sweet potato	5.41 a
1st Aerobic after Soy bean	5.76 a

6.3.3. Long-term aerobic rice yields

Tables 6.3.7a,b give the yields in the continuous aerobic rice fields and in the flooded rice fields from 2001 to 2007. In the DS, the yield under aerobic conditions consistently declined compared with the yield under flooded conditions from 2001 to 2005. Also in absolute terms, the continuous aerobic rice yields declined, under both N-fertilized and 0-N conditions. However, in both 2006 and 2007, aerobic rice yields spectacularly increased and even attained the highest recorded yield of 5.2 t ha^{-1} under N-fertilized conditions in 2007. Unfortunately, there were no flooded treatments to compare with. In the WS, no consistent yield decline was found over the period 2001-2007.

In both the DS and the WS, the sustainability of aerobic rice under 0-N conditions is remarkable: aerobic rice yield in the DS was still 3 t ha^{-1} after 13 crops, and 2.4 t ha^{-1} in the WS after 12 crops.

Table 6.3.7a. Yield of Apo under continuous aerobic and under flooded conditions, and ratio of aerobic over flooded yield, IRRI farm, 2001-2007 DS.

	2001DS	2002DS	2003DS	2004DS	2005DS	2006DS	2007DS
Aerobic +N	4.37	5.06	3.84	3.78	3.05	4.45	5.19
Aerobic –N	3.08	3.29	3.16	2.73	2.47	2.47	3.02
Flooded +N	5.06	7.33	6.81	6.33	6.79	-	-
Flooded –N	3.63	3.81	4.06	4.02	4.86	-	-
A/F +N (%)	86	69	56	60	45	-	-
A/F -N (%)	85	86	78	68	51	-	-

Table 6.3.7b. Yield of Apo under continuous aerobic and under flooded conditions, and ratio of aerobic over flooded yield (A/F), IRRI farm, 2001-2007 WS.

	2001WS	2002WS	2003WS	2004WS	2005WS	2006WS	2007WS
Aerobic +N	3.6	3.49	4.2	3.36	3.18	3.16	-
Aerobic –N	2.59	3.13	3.74	2.54	2.57	2.36	-
Flooded +N	4.57	4.77	6.04	4.22	5.71	-	-
Flooded –N	3.65	3.24	4.47	3.06	5.03	-	-
A/F +N (%)	79	73	70	80	56	-	-
A/F -N (%)	71	97	84	83	51	-	-

6.3.4. Causes for yield decline

A large number of pot and micro-plot experiments were done with the soil from the long-term aerobic rice experiment at IRRI to determine the causes of the yield decline and propose remedial measures. Pot experiments were done in greenhouses and screenhouses at IRRI, and variety Apo was used in all experiments.

Oven heating

Soil sterilization by oven heating to remedy "soil sickness" (Anderson and Magdoff 2005; Kirkegaard et al. 1995; Sasaki et al. 2006). Six pot experiments with different soil heating treatments were conducted at the IRRI farm using soil collected from the top 25 cm of three fields that were previously grown to aerobic rice or to flooded rice. Details are reported by Lixiao Nie et al. (2007), and here we summarize the main findings. Soils were taken from fields where aerobic rice was grown continuously for 10 and 5 seasons, and from fields where flooded rice was grown. Soil heating was done at 120 °C for 12 hours.

Oven heating of soil with an aerobic history increased rice plant growth significantly over the unheated control (Table 6.3.8). The response of plant growth to soil heating was highest in leaf area, followed by total biomass and stem number. Although soil heating does not reveal the cause of soil sickness and cannot differentiate between biotic (e.g., soil-borne pathogens) or abiotic (e.g., soil chemical) causes of soil sickness, the evidence from the various pot experiments (not shown here, see Lixiao Nie et al., 2007) suggests that abiotic factors are more likely to cause "soil sickness" in our field experiment.

Table 6.3.8. Plant growth of Apo grown aerobically without soil heating (control) and after soil heating using aerobic and flooded soils from IRRIs' long-term aerobic rice experiment. Source: Lixiao Nie et al., 2007.

Parameter	Control	Heated	Increase (%)
10th-season aerobic soil			
Stem number per pot	3.2 b	19.8 a	519
Plant height (cm)	37.4 b	67.2 a	80
Leaf area (cm^2 pot^{-1})	60 b	991 a	1552
Total biomass (g pot^{-1})	0.6 b	7.5 a	1150
5th-season aerobic soil			
Stem number per pot	3.0 b	10.4 a	247
Plant height (cm)	35.8 b	57.8 a	61
Leaf area (cm^2 pot^{-1})	66 b	394 a	497
Total biomass (g pot^{-1})	0.7 b	3.1 a	343
Flooded soil			
Stem number per pot	9.0 a	10.4 a	16
Plant height (cm)	57.0 a	56.0 a	-2
Leaf area (cm^2 pot^{-1})	296 a	356 a	20
Total biomass (g pot^{-1})	2.6 a	3.5 a	35

Within a row, means followed by different letters are significantly different at 0.05 probability level according to least significant difference (LSD) test.

Nutrient supply

Soil oven heating was shown above to alleviate soil sickness caused by continuous copping of aerobic rice. Heating can kill pathogenic nematodes, fungi, and bacteria, but can also facilitate the release of nutrients from the soil by enhancing mineralization or transforming nutrients into more available forms. Using micro-plots and pot experiments, we explored the effects of N, P, K and micronutrients on growth and yield of aerobic rice grown in soil from IRRI's long term aerobic rice experiment. Details of the experiments and results are reported by Lixiao Nie et al. (in prep 1), and here we summarize the key findings.

Micro-plots of 1.0 × 1.0 m were established in 9th-season aerobic rice field (2005 DS) of IRRI's long-term aerobic rice experiment. The treatments were Yoshida nutrient solution (Yoshida et al., 1976), Yoshida solution without NPK, and control. In the micro-plots with full Yoshida solution, the total amount of elements received was 144 kg N, 36 kg P, 144 kg K, 188 kg Ca, 188 kg Mg, 2.35 kg Mn, 0.235 kg Mo, 0.94 kg B, 0.047 kg Zn, 0.047 kg Cu, and 9.4 kg Fe per hectare. The application of Yoshida solution without NPK increased grain yield over the control, but the difference was not significant (Table 6.3.9). The application of the full Yoshida solution, however, increased yield by 47% and 24% over the control and Yoshida solution without NPK, respectively. These results suggest that the combination of N, P, and K rather than micronutrients alleviated soil sickness caused by continuous cropping of aerobic rice.

Table 6.3.9. Biomass, yield, and yield components of Apo grown with Yoshida nutrient solution without NPK and with complete Yoshida solution, in comparison with control, IRRI farm, 2005 DS.

Parameter	Control	Yoshida solution without NPK	Yoshida solution
Grain yield (t ha^{-1})	3.18 b	3.77 b	4.69 a
Aboveground biomass (g m^{-2})	809 b	903 b	1067 a
Harvest index (%)	34.8 a	37.2 a	39.2 a
Panicles m^{-2}	254 b	262 b	304 a
Spikelets $panicle^{-1}$	87.0 b	94.9 ab	99.3 a
Spikelets m^{-2} ($x10^3$)	22.0 c	24.8 b	30.2 a
Grain filling (%)	68.5 a	71.4 a	73.6 a
1000-grain weight (g)	18.6 a	18.9 a	18.8 a

Within a row, means followed by different letters are significantly different at 0.05 probability level according to Least Significant Difference (LSD) test.

In pot experiment 1, soil was collected from the 11th-season aerobic rice field and from a flooded field. For both the aerobic and the flooded soil, the treatments were an unfertilized control, oven heating at 120ºC for 12 hours, and nutrient additions of 0.90 g N as urea, 0.64 g P as solophos, and 1 g K as potassium chloride per pot. Pot experiment 2 used the same soils, and had a control, 1 oven-heating, and five nutrient treatments: 0.90 g N as urea (1); 0.32 g P as solophos (2); 2 g K as potassium chloride (3); Yoshida solution without NPK (4); 0.90 g N as urea, plus 0.32 g P as solophos, plus 2 g K as potassium chloride, plus Yoshida solution without NPK (all values per pot). The total amount of nutrients in Yoshida solution without NPK was 96 mg Ca, 96 mg Mg, 1.2 mg Mn, 0.12 mg Mo, 0.48 mg B, 0.024 mg Zn, 0.024 mg Cu, and 4.8 mg Fe per pot. In both pot experiments, Apo was grown aerobically in all pots.

In pot experiment 1, the application of N, P, and K improved plant growth and leaf N nutrition significantly over the control in both aerobic and flooded soils (Table 6.3.10). However, the plant response was greater in the soil from the aerobic field than in the soil from the flooded field. This confirms that aerobic soil used in this study was "sick" compared with flooded soil, and that the addition of NPK was effective to reduce the soil sickness. Oven heating also improved plant growth over the control, in both soils. Again, the response was greater in aerobic soil than in flooded soil. In pot experiment 2, both urea and solophos increased plant growth significantly over the control (Table 6.3.11). The application of Yoshida solution and NPK, and soil heating, also increased plant growth, and the effect was larger than in the urea and solophos treatments. The application of Yoshida solution without NPK and the application of potassium did not consistently increase plant growth over the control. The results eliminated the possibility of K in alleviating soil sickness.

Table 6.3.10. Plant growth of Apo grown with NPK application and under oven heating in comparison with the control, pot experiment 1, IRRI.

Parameter	Control	NPK	Oven heating
Soil from aerobic field			
Plant height (cm)	41.7 b	63.5 a	63.8 a
Stem number per pot	7.5 c	25.0 b	38.8 a
Leaf area (cm^2 pot^{-1})	72 c	729 b	1306 a
Total biomass (g pot^{-1})	1.74 c	11.13 b	23.70 a
SPAD value	30.5 b	40.1 a	40.9 a
Soil from flooded field			
Plant height (cm)	57.3 b	67.8 a	65.7 a
Stem number per pot	20.5 b	26.8 a	28.0 a
Leaf area (cm^2 pot^{-1})	479 b	923 a	854 a
Total biomass (g pot^{-1})	9.24 b	14.31 a	14.38 a
SPAD value	37.4 b	41.6 a	40.6 a

Within a row, means followed by different letters are significantly different at 0.05 probability level according to Least Significant Difference (LSD) test.

Table 6.3.11. Plant growth of Apo under different nutrient treatments and oven-heating, in comparison with the control, pot experiment 2, IRRI.

Treatment	Plant height (cm)	Stem number pot^{-1}	Leaf area (cm^2 pot^{-1})	Total biomass (g pot^{-1})
Control	57.8 e	6.8 d	318 d	3.8 d
Urea	72.2 b	9.2 c	675 c	5.3 c
Solophos	66.8 c	9.3 c	604 c	6.0 c
Potassium chloride	61.0 d	6.3 d	302 d	3.2 d
Yoshida minus NPK	57.5 e	6.7 d	342 d	4.1 d
(1) + (2) + (3) + (4)	75.8 a	11.7 b	933 b	7.8 b
Oven heating	76.5 a	13.5 a	1059 a	10.9 a

Within a column, means followed by different letters are significantly different at 0.05 probability level according to Least Significant Difference (LSD) test.

We concluded that micronutrients were not effective in increasing plant growth in pot experiments nor of increasing grain yield in field micro-plot experiments. Plant growth was not improved with the application of K or of P fertilizers (Ca-Mg phosphate and rock phosphate) and P chemical reagents (monosodium phosphate dihydrate) (Pot experiments and data not shown; Lixiao Nie et al. in prep 1). However, slight growth increase was observed with the application of calcium superphosphate, and large growth increase with solophos. Solophos and calcium superphosphate contained 2.9% and 1.7% N, respectively, and we can not rule out the possibility that the added N in these P fertilizers contributed to improved crop performance. From other pot experiments (data not shown; Lixiao Nie et al. in prep 1), however, it was concluded that P nutrition was not associated with the soil sickness in IRRI's continuous aerobic rice experiment.

Nitrogen form

From the nutrient experiments reported above, it was concluded that N application may alleviate the effects of soil sickness in IRRI's continuous aerobic rice experiment. Follow-up pot experiments were conducted using soil collected from the 11th-season aerobic rice field and from a flooded field of IRRI's long-term aerobic rice experiment (Lixiao Nie et al. in prep 2). In all experiments, Apo was grown aerobically in all pots. In experiment 1, we used only soil from the aerobic fields. Beside an oven-heated treatment, we had 25 nutrient treatments consisting of 5 forms of N chemical reagents (ammonium sulfate ($(NH_4)_2SO_4$), urea ($CO(NH_2)_2$), ammonium nitrate (NH_4NO_3), ammonium chloride (NH_4Cl), and potassium nitrate (KNO_3)) by 5 N rates (0, 0.3, 0.6, 0.9, and 1.2 g N/pot). In experiment 2, we used both soils. Beside an oven-heated treatment, we had 2 nutrient treatments: 1.2 g N/pot as urea, and 1.2 g N/pot as ammonium sulfate.

In experiment 1, increasing N rates increased plant growth in the aerobic soil, when N was applied as ammonium sulfate and urea (Table 6.3.12). Compared with urea, ammonium sulfate was more effective in promoting plant growth. Plant growth was not consistently improved by the application of ammonium nitrate. Though most growth parameters increased when N was applied as ammonium chloride, total biomass did not respond significantly. Potassium nitrate had a negative effect on plant growth, even to the extent that plants died at the rate of N4. In experiment 2, both ammonium sulfate and urea application significantly improved plant growth in the aerobic soil (Table 6.3.13). However, the effect of ammonium sulfate was larger than that of urea. Urea had no effect on plant growth in the soil from flooded fields, whereas the effect of ammonium sulfate in the soil from flooded fields was much smaller than that in the soil from aerobic fields. Oven-heating of the soil increased plant growth in both soils.

Table 6.3.12. Aboveground biomass (g pot^{-1}) of Apo grown under five N forms with five N rates and soil oven-heating treatment in pot experiment 1, IRRI.

N rates	$(NH4)_2SO_4$	NH_4Cl	$CO(NH_2)_2$	NH_4NO_3	KNO_3
N0	3.42 d	3.42 bc	3.42 b	3.42 b	3.42 b
N1	4.44 d	2.88 c	3.89 b	3.13 b	1.90 c
N2	7.03 c	3.80 bc	4.55 b	2.98 b	1.77 c
N3	7.19 c	5.14 b	4.57 b	2.55 b	0.60 d
N4	11.90 b	4.81 b	4.82 b	2.84 b	0.00 d
Oven heating	15.38 a	15.38 a	15.38 a	15.38 a	15.38 a

Within a column under each parameter, means followed by different letters are significantly different at 0.05 probability level according to Least Significant Difference (LSD) test.

Table 6.3.13. Plant growth of Apo grown under urea and ammonium sulfate application and soil oven-heating in comparison with the untreated control in pot experiment 2, IRRI.

Parameter	Control	Urea	Ammonium sulfate	Oven-heated
Plant height (cm)	45.2 c	58.7 b	77.5 a	80.8 a
Stem number per pot	4.7 d	8.8 c	19.7 b	22.2 a
Leaf area (cm^2 pot^{-1})	105 d	300 c	951 b	1423 a
Root dry weight (g pot^{-1})	0.27 d	0.72 c	1.52 b	2.73 a
Total biomass (g pot^{-1})	1.23 d	3.41 c	10.03 b	16.71 a
Plant height (cm)	68.8 c	74.3 b	75.7 ab	79.2 a
Stem number per pot	11.5 b	14.3 b	21.3 a	20.7 a
Leaf area (cm^2 pot^{-1})	589 b	690 b	923 a	1106 a
Root dry weight (g pot^{-1})	1.48 ab	1.00 c	1.23 bc	1.66 a
Total biomass (g pot^{-1})	6.92 c	7.27 bc	9.32 ab	10.87 a

Within a row, means followed by different letters are significantly different at 0.05 probability level according to Least Significant Difference (LSD) test.

We concluded that the application of nitrogen could reverse the decline in crop growth in continuously cropped aerobic rice in IRRI's long-term field experiment. Though in the long-term experiment, 150 and 70 kg urea-N ha^{-1} are continuously applied in the DS and WS, respectively, the extra N applications significantly improved the plant growth in our pot experiments. Ammonium sulfate was much more effective on improving plant growth than urea or other sources of N.

6.3.5. Yield "collapse"

Beside the gradual yield decline under continuous cropping of aerobic rice reported above, we encountered two cases of "immediate yield collapse" in fields cropped to aerobic rice for the very first time. One field experiment at Dapdap, Tarlac, (same site as where other successful experiments on aerobic rice were conducted, see paragraphs on "Water and nutrient dynamics" and on "Crop establishment") and one at the IRRI farm, on water x nitrogen interaction showed complete yield failures. Though our study on "yield collapse" is not part of the CPWF-project, we present the results of the Dapdap experiment here to "flag the problem".

A water by N experiment was conducted in the dry season 2004 and 2005 at Dapdap (120.73ºN, 15.62ºE, 26 m asl) in Central Luzon, The Philippines. The soil was loamy sand with 71% sand, 22% silt, and 7% clay in the top soil (15 cm). Before our experiment, the soil was cropped to rainfed lowland rice under conditions of intermittent flooding (because of irregular rainfall and high soil water permeability). The water treatments were: irrigation twice per week (W1), once per week (W2) and once in 2 weeks (W3, modified in 2004 to weekly from panicle initiation on). During the critical flowering stage all water treatments were irrigated twice per week for 4 to 5 weeks. Irrigation was applied by sprinklers early in the season and by flash flooding later in the season. The N treatments were: 0 kg N ha^{-1} (N1), 60 kg N ha^{-1} (N2), 120 kg N ha^{-1} (N3), 160 kg N ha^{-1} (N4), and 200 kg N ha^{-1} (N5). In 2005, N5 was cancelled and N4 adjusted to 165 kg N ha^{-1}. There was complete yield failure on all treatments in both years (Table 6.3.14), even though up to 200 kg urea-N ha^{-1} and some 1000 mm water were applied. The investigation of the possible causes of yield collapse at Dapdap, and in the similar experiment at IRRI (data not shown), is in full progress and focuses on both biotic (nematodes, root fungi) and abiotic (micro- and macro-nutrients, soil pH) factors. From the initial analysis of the Dapdap experiment, it is concluded that the yield collapse was not a direct result of reduced water and/or N availability. There was good evidence for root knot nematodes and potentially micronutrient imbalances as causal factors.

Table 6.3.14. Yield (t ha^{-1}), total straw biomass (t ha^{-1}), and harvest index, per water (W) and nitrogen (N) treatment, Dapdap, 2004 and 2005.

	Yield				Straw				Harvest index			
	W1	W2	W3	Av	W1	W2	W3	Av	W1	W2	W3	Av
2004												
N1	0.11^{ab}	0.02^{a}	0.03^{a}	0.05^{a}	2.8^{b}	3.0^{b}	3.0^{a}	2.9^{b}	0.07^{a}	0.01^{a}	0.03^{a}	0.04^{a}
N2	0.32^{a}	0.04^{a}	0.11^{a}	0.16^{a}	4.2^{a}	4.1^{ab}	4.0^{a}	4.1^{a}	0.07^{a}	0.01^{a}	0.03^{a}	0.04^{a}
N3	0.04^{b}	0.02^{a}	0.04^{a}	0.03^{a}	4.3^{a}	4.3^{a}	3.8^{a}	4.1^{a}	0.01^{b}	0.01^{a}	0.02^{a}	0.01^{a}
N4	0.04^{b}	0.06^{a}	0.07^{a}	0.06^{a}	4.2^{a}	4.4^{a}	3.8^{a}	4.1^{a}	0.01^{b}	0.02^{a}	0.02^{a}	0.02^{a}
N5	0.21^{ab}	0.04^{a}	0.18^{a}	0.14^{a}	5.2^{a}	4.6^{a}	4.1^{a}	4.7^{a}	0.05^{ab}	0.01^{a}	0.03^{a}	0.03^{a}
Av	0.14^{A}	0.04^{A}	0.08^{A}		4.1^{A}	4.1^{A}	3.7^{A}		0.04^{A}	0.01^{A}	0.03^{A}	
2005												
N1	0.36^{b}	0.22^{a}	0.15^{a}	0.24^{b}	2.9b	3.3^{c}	2.9^{c}	3.0^{c}	0.10^{b}	0.09^{a}	0.07^{a}	0.09^{a}
N2	0.92^{b}	0.26^{a}	0.45^{a}	0.54^{ab}	5.0a	3.8^{bc}	4.4^{ab}	4.4^{ab}	0.18^{ab}	0.08^{a}	0.10^{a}	0.12^{a}
N3	0.36^{b}	0.26^{a}	0.04^{a}	0.22^{b}	4.6a	4.8^{ab}	3.4^{bc}	4.3^{b}	0.13^{ab}	0.06^{a}	0.01^{a}	0.07^{a}
N4	1.79^{a}	0.71^{a}	0.10^{a}	0.86^{a}	5.2a	5.0^{a}	4.7^{a}	5.0^{a}	0.24^{a}	0.10^{a}	0.03^{a}	0.12^{a}
Av	0.86^{A}	0.36^{B}	0.18^{B}		4.4^{A}	4.2^{A}	3.9^{A}		0.16^{A}	0.08^{B}	0.05^{B}	

Data in columns followed by the same a minor letter are not significantly different (P = 0.05). Data in rows followed by the same capital letter are not significantly different (P = 0.05).

6.3.6. Conclusion

In the long-term aerobic rice field experiment at the IRRI farm, yield of variety Apo declined under aerobic field conditions relative to flooded conditions in the first 10 season of continuous cropping. Part of this relative yield decline can be attributed to yield increase under flooded conditions after the third season, but part is caused by absolute yield decrease under aerobic conditions. The yield in the same year in a "new" aerobic field (after continuous flooded cropping) was about 2.5 t ha^{-1} higher than in a seventh-season continuous aerobic field. Compared with the flooded fields, nematodes of the *Meloidogyne graminicola* species were much higher in the aerobic fields, but no correlation with yield was established. The typical patchiness related to the occurrence of nematodes was not observed.

Yield decline could be reversed by crop rotations, fallowing, and flooding. Flooding for three consecutive seasons and fallowing for two consecutive seasons were equally effective in restoring aerobic rice yields. Cropping with upland crops (maize, sweet potato, and soybean) for two consecutive seasons was more effective than fallowing for two consecutive seasons.

Pot and micro-plot (within the field experiment) experiments showed that yield decline could not be reversed by the application of micro-nutrients, P, or K. However, crop growth was consistently improved by the application of N fertilizer in the form of urea or Ammonium sulfate. Ammonium sulfate, however, was much more effective than urea. The reasons for improved plant growth with additional N application are not yet understood. It may have to do with changes in soil pH and subsequent changes in nutrient availability. It is also possible, however, that biotic stresses (such as nematodes) limit the crop's ability to take up nutrients and that extra N application may overcome such a limitation.

Dry season aerobic rice yields increased dramatically after 10 seasons of continuous cropping. Yields in the 11^{th} and 13^{th} season were 1.4 t ha^{-1} and 2.1 t ha^{-1} higher, respectively, than in the 9^{th} continuous season. This suggests some self-regenerating mechanism in the system but needs more study to confirm. The increase in aerobic rice yields after 10 seasons was not obvious in the wet season with lower yield levels than in the dry season.

We found preliminary evidence (data not shown; see Lixiao Nie et al., in prep 2) of genotypic variation to "soil sickness" associated with continuous aerobic rice cropping. This needs to be further explored in follow-up studies to see if germplasm improvement can confer some degree of tolerance to "soil sickness".

The geographic extent of possible yield decline under continuous cropping or of immediate yield "collapse" in Asia is not known. The IRRI experiment is the only long-term aerobic rice experiment in existence. More long-term experiments are needed to determine the extent of the problem. Beside a few sites in the Philippines, we have not encountered any cases of immediate yield "collapse" in China or India. Extremely low yields have also been reported in some of our trials in Laos and Thailand, but these were most likely caused by extreme droughts. The occurrence of nematodes, however, may be more widespread than assumed so far in rice fields that are not permanently flooded (Janice Thies, personal communication, from an inventory in S Asia). It is proposed to conduct diagnostic surveys of "soil health" in current and potential target areas for aerobic rice.

6.4. Objective 4: Crop establishment

6.4.1. Method

We focused our experiments on seed rate and row spacing. We analyzed and synthesized field experiments we performed in 2004, and performed new experiments during the STAR project in 2005-2006. In most experiments, the "crop establishment" factor was part of a multi-factor experiment involving different N regimes or irrigation water regimes. Table 6.4.1 gives an overview of the location of the experiments.

Table 6.4.1. Sites of crop establishment (seed rate, row spacing) experiments per country

Activity/ Country	Philippines	China	India	Laos	Thai
Seed rate		Beijing: Xibeiwang, Shanzhuang	WTC-IARI station, Delhi		
Row spacing	San Ildefonso, Dapdap, Munoz				

China. Two field experiments were conducted in 2004 at Xibeiwang village (39°95′ N, 116°4′ E; 43 m asl), Beijing. In the first, three fertilizer N applications (120 kg N ha^{-1} single application as coated urea; 120 kg N ha^{-1} three-split application as regular urea; and 0 N control) were combined with three seed rates (60, 90, and 120 kg ha^{-1}). Aerobic rice HD297 was dry sown at a depth of 3 cm with a row spacing of 27.5 cm. In the second experiment, seed rates of 60 and 120 kg ha^{-1} were combined with row spacings of 27.5 and 33 cm. Fertilizer N application was 120 kg N ha^{-1} in three-split application using regular urea. The fields of both experiments had 61% sand, 28% silt, and 11% clay (groundwater deeper than 20 m).

In 2006, we introduced two seed rates in the water x nitrogen experiment at Shangzhuang near Beijing: 135 (D2) and 67.5 (D1) kg ha^{-1} (see paragraph "Water and nutrient dynamics" above for full experiment explanation). The row spacing was kept unchanged at 30 cm; aerobic rice variety HD297 was used.

India. A water x variety x seed rate experiment was conducted at the WTC-IARI station, Delhi, in 2006-2007. The seed rates were 20, 30, 40, and 80 kg ha^{-1} (Note that 80 kg ha^{-1} was used in the irrigation water experiments reported above). The same 3 irrigation water treatments were used as in the water experiments: irrigation water applied (through flash flooding) when soil water tension at 20 cm depth reached "0 kPa" which means keeping the soil close to saturation (I0), when soil water tension reached 20 kPa (I20), and when soil water tension reached 40 kPa (I40). The varieties used were Pusa Sugandh 3 and Pusa Rice Hybrid 10. Seeds were dry sown in rows spaced 25 cm apart.

Philippines. The effect of row spacing was studied in N fertilizer x row spacing interaction experiments at San Ildefonso (Bulacan), Munoz-PhilRice station, and Dapdap village (Tarlac), in 2004-2005. At all sites, rice variety Apo was dry seeded, and the row spacings were 25, 30, and 35 cm. More experimental details are presented in the paragraph "Water and nutrient dynamics".

6.4.2. Results China

Yields of HD297 in the experiment on seed rate x fertilizer N at Xibeiwang in 2004 varied from 3.2 to 3.9 t ha^{-1} (Table 6.4.2). There were no significant differences in yield among neither the seed rate treatments nor the fertilizer N treatments. Like in the other fertilizer N experiments near Beijing (see paragraph "Water and nutrient dynamics" above), there was no effect of N application over the 0 N control. In the second experiment, on seed rate x row spacing, yields were 3.5 to 3.9 t ha^{-1} (Table 6.4.3). Yields were not affected by seed rate nor by row spacing.

Table 6.4.2. Biomass, grain yield, and harvest index of aerobic rice HD297 grown under different fertilization and seeding rate treatments, Xibeiwang, Beijing, 2004.

Fertilizer	Seeding Rate (kg ha^{-2})	Aboveground Biomass (g m^{-2})	Grain yield ($g\ m^{-2}$)	Harvest Index (%)
Coated urea	60	1090 bcd	397 a	39 a
	90	1206 abc	368 ab	31 abc
	120	1262 a	344 ab	27 c
split N	60	1112 abcd	377 ab	34 abc
	90	1238 ab	361 ab	33 abc
	120	1052 cd	316 b	31 abc
CK	60	1086 bcd	392 a	36 abc
	90	1010 d	349 ab	37 ab
	120	1149 abcd	336 ab	29 abc

Different lowercase letters within a column for the same year indicate significant differences at a $P<0.05$ level.

Table 6.4.3. Yield and yield components of aerobic rice HD297 grown at different seeding rate and row spacing treatments, Xibeiwang, Beijing, 2004.

Seeding rate (kg ha^{-2})	Row Spacing (cm)	Yield (g m^{-2})	Panicle m^{-2}	Spikelet $panicle^{-1}$	% grain filling	1000-grain weight (g)
60	27.5	376.6 a	266.9 b	80.6 ab	78.6 a	28.4 ab
	33	396.1 a	212.0 c	86.9 a	71.6 bc	29.0 a
90	27.5	361.0 a	295.3 a	74.9 b	66.5 c	27.4 b
	33	349.9 a	226.8 c	76.9 b	68.4 bc	28.5 a

Different lowercase letters within a column indicate significant differences at a $P<0.05$ level

At Shangzhuang, reducing the seed rate from 135 to 67.5 (D1) kg ha^{-1}, did not significantly affect yield except in the W1N0 treatment (highest irrigation water application, 0 N application) where yield was reduced with about 1 t ha^{-1} (Figure 6.4.1). Among the yield components, the number of panicles m^{-2} and the number of spikelets $panicle^{-1}$ were most affected, though in opposite directions so that the reduction in the first was compensated by an increase in the second (Figures 6.4.2a,b).

Figure 6.4.1. Yield of HD297 at two seed rates (D1, D2) in four water x nitrogen treatments, Shangzhuang, near Beijing, 2006. Treatment abbreviations are explained in the methods sections of "Water x nutrient interaction" paragraph.

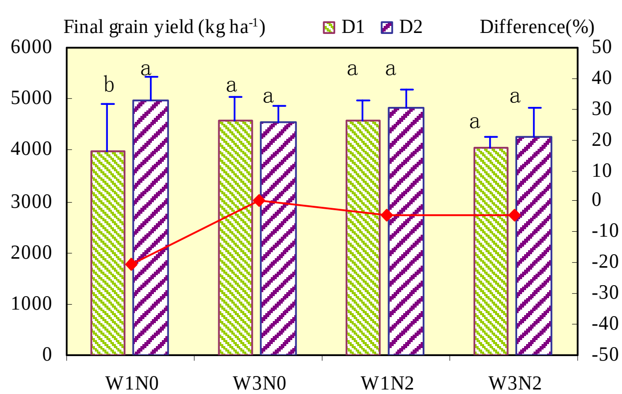
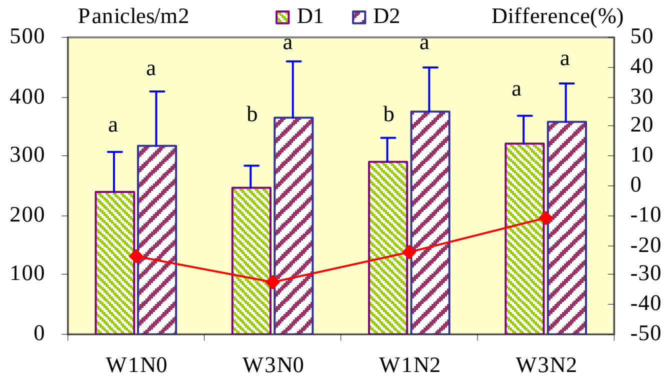
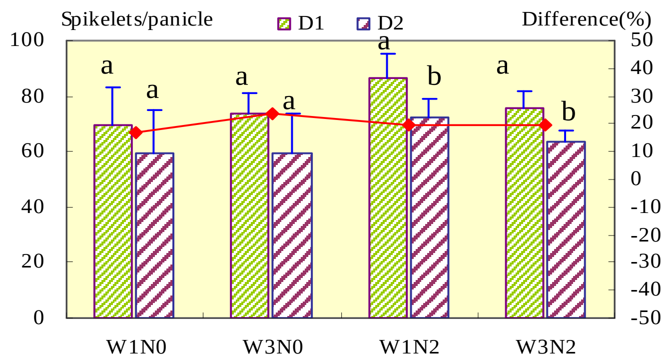


Figure 6.4.2a. Number of panicles m^{-2} (A) and number of spikelets $panicles^{-1}$ (B) of HD297 at two seed rates (D1, D2) in four water x nitrogen treatments, Shangzhuang, near Beijing, 2006. Treatment abbreviations are explained in the methods sections of "Water x nutrient interaction" paragraph.



A

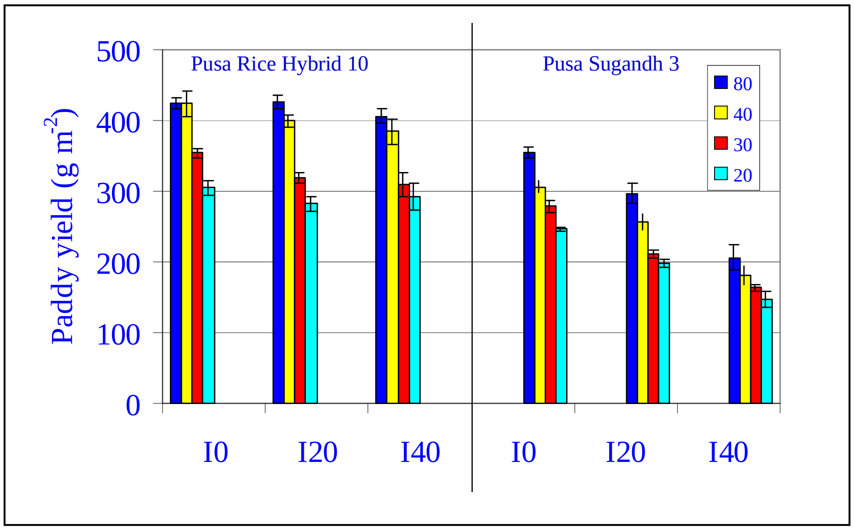


B

6.4.3. Results India

In 2006, yields of Pusa Rice Hybrid 10 were 2.9-4.2 t ha^{-1}, whereas those of Pusa Sugandh 3 were 1.5-3.5 t ha^{-1} (Figure 6.4.3; data of 2007 still being analyzed). The hybrid variety showed little yield loss with increasing soil water tension, whereas yields of the inbred variety dropped fast with increasing soil water tension. In the hybrid variety, yields were at par with 80 and 40 ka ha^{-1} seed rate, but yields dropped significantly with seed rates less than 40 kg ha^{-1}. In the inbred variety, yields decreased significantly with decreasing seed rate below 80 ka ha^{-1}.

Figure 6.4.3. Yield of two rice varieties under three irrigation treatments (I0, I20, I40) and four seed rates, WTC-IARI station, Delhi, 2006.



6.4.4. Results Philippines

Information on groundwater depth and soil water tensions during the experiments, and the effect of fertilizer N on yield, was presented in the paragraph "Water and nutrient dynamics". More detailed results are presented by Lampayan et al. (in prep). In both experiments, there was no significant effect of row spacing on yield (Table 6.4.4, Table 6.4.5).

Table 6.4.4. Grain yield and total biomass (averaged over N rates) of Apo in different row spacings at San Ildefonso and Dapdap, 2004 and 2005 wet seasons.

Site and year	Row spacing	Yield (t ha^{-1})	Total biomass at harvest (t ha^{-1})
San Ildefonso, 2004	RS_{25}	3.76 a	14.22 b
	RS_{30}	3.72 a	12.74 a
	RS_{35}	3.69 a	12.04 a
San Ildefonso, 2005	RS_{25}	3.85 ab	10.12 b
	RS_{30}	3.91 b	10.10 b
	RS_{35}	3.61 a	8.94 a
Dapdap, 2004	RS_{25}	3.65 a	10.58 b
	RS_{30}	3.65 a	9.78 a
	RS_{35}	3.69 a	9.30 a
Dapdap, 2005	RS_{25}	3.20 a	7.45 b
	RS_{30}	3.17 a	7.29 ab
	RS_{35}	3.15 a	6.48 a

Means followed by a different letter (within same site and season) are significantly different at the 5% level.

Table 6.4.5. Effects of row spacings on grain yield (averaged over N splits) and yield components of Apo cultivar in PhilRice during 2004 wet season and 2005 dry season.

Year	Row spacing	Yield (t ha^{-1})	Total biomass at harvest (t ha^{-1})
2004	RS_{25}	3.49 a	10.2 b
	RS_{30}	3.40 a	9.3 a
	RS_{35}	3.58 a	9.1 a
2005	RS_{25}	5.79 a	11.6 a
	RS_{30}	5.82 a	11.6 a
	RS_{35}	5.84 a	11.4 a

Means followed by a different letter (within same site and season) are significantly different at the 5% level.

6.4.5. Conclusion

Direct dry-seeded aerobic rice (varieties Apo in the Philippines, and HD297 in China) does not seem to be very responsive to row spacing and seed rate (within the limits tested). Both in the Chinese and the Philippine experiments, row spacing between 25 and 35 cm gave statistically the same yields. In the Chinese experiments, yields were the same with differences in seeding rate in the 60-135 kg ha^{-1} range. In the India experiment, the better performing variety Pusa Rice Hybrid 10 had statistically same yields with seed rates of 40 and 80 ka ha^{-1}, but below 40 kg ha^{-1}, yields declined fast. In practice, the "unresponsiveness" of aerobic rice to seed rate and row spacing means that farmers are rather flexible in choosing their own rates and spacings (within the limits studied). A close row spacing and high seed rate may increase the competitiveness of aerobic rice to weeds but may increase seed costs. A wider row spacing may facilitate interrow cultivation, such as mechanical weeding, and reduce seed costs.

6.5. Objective 5: Target domain

Aerobic rice is an option to farmers, in either irrigated or rainfed areas, who would like to grow rice but where water availability at the farm level is too low, or where water is too expensive, to grow flooded rice. There are many water-saving technologies for rice, and the most suitable or "attractive" technology depends on the type and level of water scarcity, soil properties to hold water, availability of suitable rice varieties, the irrigation infrastructure (if present), and the socio-economics of their production environment (Bouman et al., 2006, 2007). In this paragraph, we review these factors to describe the target domain for aerobic rice, with the exception of "irrigation infrastructure" as that was beyond the scope of our CPWF project. The methods we used were field experiments, simulation modeling, GIS, and household surveys, with a focus on China (Table

6.5.1). We also report briefly on the initial results of extrapolation domain analysis that was part of the CPWF's Impact project.

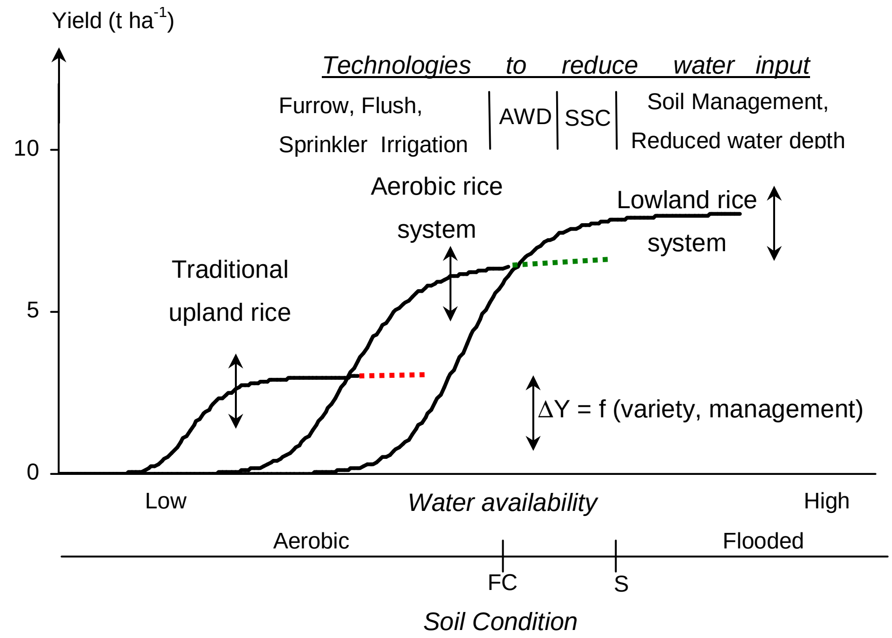
Table 6.5.1. Sites of target domain analysis per country

Activity/country	Phil	China	India	Laos	Thai
Field experiment		Changping, Beijing			
Variety zoning		Whole country			
Modeling, GIS		Beijing, Tianjin, Shandong, Hebei, Henan			
Household survey		Kaifeng, Fengtai, Yingshang, Beijing			
Extrapolation domain	Whole country	Whole country	Whole country	Whole country	Whole country

6.5.1. Water availability and soil type

Figure 6.5.1 presents a gradient in water availability to grow a crop at the field level, and some appropriate technologies to grow rice. Going from right to left along the water-availability axis, water gets increasingly scarce and yields decline. On the far right-hand side of the water axis, water is amply available and farmers can practice continuous flooding and obtain the highest yields. With decreasing water availability, appropriate technologies are saturated soil culture or alternate wetting and drying. With further decreasing water availability, trying to keep growing lowland rice (aiming for saturated soil conditions and at least partial flooding) is not be possible anymore and aerobic rice becomes attractive. On the far left-hand side, water is extremely short, such as in rainfed uplands, and yields are very low. Here, sturdy and drought-resistant upland varieties and upland cropping systems become appropriate.

Figure 6.5.1. Schematic presentation of appropriate water-saving technologies along a relative water availability axis. AWD = alternate wetting and drying, SSC = saturated soil culture, FC = field capacity, S = saturation point, ΔY = change in yield. Source: Bouman et al. (2007).



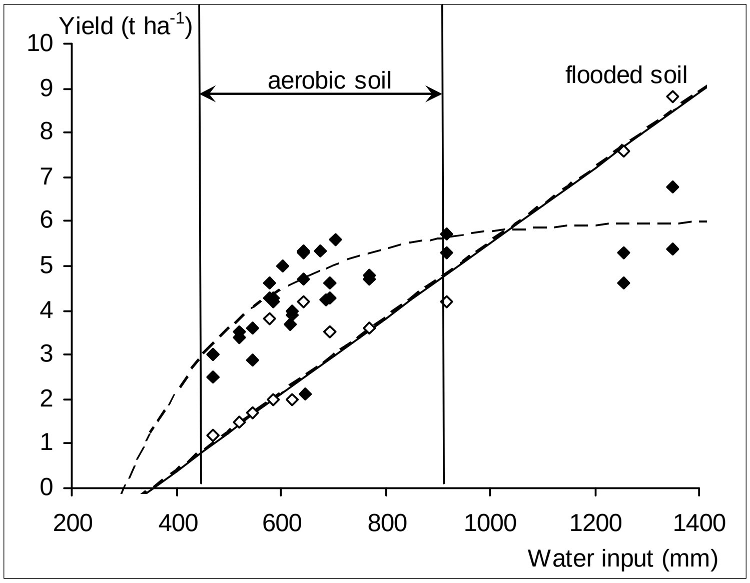
How much less water is used under aerobic conditions than under flooded conditions depends mostly on the seepage and percolation (SP) losses under flooded conditions and on the deep percolation losses of irrigation water under aerobic conditions. Typical SP rates of flooded rice fields vary from as little as 1 mm d^{-1} to more than 25 mm d^{-1} (Bouman and Tuong, 2001). Under aerobic conditions, the amount of deep percolation depends on the combination of soil water holding capacity and method of irrigation, and is reflected in the irrigation application efficiency (EA). With a precise dosage and timing of irrigation in relation to crop transpiration and soil water holding capacity, the EA in flash-flood irrigation can be up to 60% (Doorenbos and Pruit, 1984). If furrow irrigation (or raised beds) is used, the EA can go up to 70%, and with sprinkler irrigation up to 80% or more. Assuming an average growth duration of 100 days, and mean ET values for rice, we can roughly calculate the "break-even" point for SP rates in flooded fields that would result in similar water requirements in aerobic fields with different irrigation methods (Table 6.5.2). When the SP rate in flooded rice is 3.5 mm d^{-1} or higher, aerobic systems with flash-flood irrigation will require less water, and if the SP rate is 0.5 mm d^{-1} or lower, only aerobic systems with sprinkler irrigation require less water. When aerobic rice systems are direct (dry) seeded, as is the typical target technology, an additional amount of water input can be saved by foregoing the wet land preparation.

Table 6.5.2. Comparison of water use in a hypothetical aerobic rice crop with that of lowland rice on different soils types characterized by their seepage (S) and percolation (P) rates. Source: Bouman et al., 2005.

Water flow process	Aerobic rice (mm)		Lowland rice (mm)		
Lowland soil SP rate	-	-	1 mm d^{-1}	5 mm d^{-1}	15 mm d^{-1}
Irrigation efficiency	85%	60%	-	-	-
Evaporation	100	100	200	200	200
Transpiration	400	400	400	400	400
Seepage and percolation	–	–	100	500	1,500
Irrigation inefficiency loss	90	335	–	–	–
Total	590	835	700	1,100	2,100

An example of the cross-over point in terms of water availability where aerobic rice gives higher yields than flooded lowland rice is given in Figure 6.5.2 for our field experiments at Changping, Beijing, (see paragraph "Water and nutrient dynamics"). Two aerobic rice varieties (HD297 and HD502) and one lowland rice variety (JD305) were grown under flooded conditions and under aerobic soil conditions with different amounts of total water input (irrigation and rainfall). Under flooded conditions with 1300-1400 mm water input at the right-hand side of the horizontal (water) axis, the lowland variety JD305 gave highest yields of 8-9 t ha^{-1}. The yield of JD305, however, quickly declined with increasing water shortage and aerobic soil conditions. With less than 900 mm water input, and under aerobic soil conditions, the aerobic rice varieties HD297 and HD502 outperformed the lowland variety. To further explore the cross-over point where aerobic rice systems are more suitable than lowland rice systems, comparisons of aerobic rice with systems such as saturated soil culture or alternate wetting and drying should be made. However, we can conclude that, in this environment, water availability for aerobic rice should be around 400-900 mm during the growing season.

Figure 6.5.2. Yield of aerobic rice varieties (black diamonds) and a lowland variety (open diamonds) under flooded and aerobic soil conditions, Changping, 2001-2004.

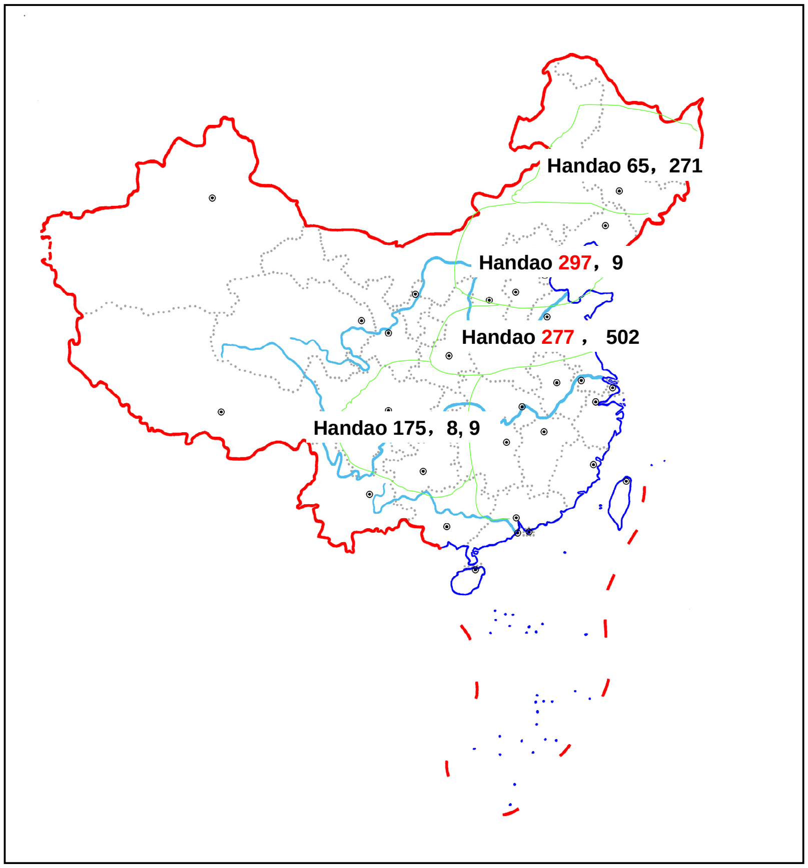


6.5.2. Target domain varieties

The availability of suitable varieties is an essential component of identifying target domains. Even when sufficient water and the right soil types are present (see paragraph "Water availability and soil type"), varieties need to be available that fit local climatic conditions and local cropping patterns. Important factors are yield potential, taste, crop growth duration to fit within the growing season or certain crop rotations, and resistance to low or high temperatures. In the Yellow River Basin in China, farmers may be able to grow just one summer crop in the northern part, but may have a double cropping system of a winter crop (wheat, barley, rapeseed) and a summer crop in the southern part. In the north, aerobic rice varieties with a long duration are needed to maximize the length of the summer season, whereas in the south, a short duration crop is needed to allow for timely establishment and harvest of the winter crop. Tolerance to low temperature in early spring is important in the north, whereas tolerance to heat during flowering may be important in both the north and the south.

Since the breeding of aerobic rice varieties has been ongoing since (at least) the early nineteen eighties, many varieties developed by a number of universities and institutes are available. In our project, we used expert knowledge by breeders to develop a target domain map for Han Dao varieties produced by China Agricultural University (Figure 6.5.3). Similar maps can be produced for other varieties.

Figure 6.5.3. Target domain and estimated distribution of aerobic rice varieties of the Han Dao series in China.



6.5.3. Mapping yield and water requirements

We used a combination of simulation modeling with ORYZA2000 and GIS to produce maps that show yield potential and water requirements in part of the Yellow River Basin and the North China Plain: Beijing, Tianjin, Shandong, Hebei, and Henan provinces. First, a crop data file was created based on the calibrations for HD297 using experimental data collected at Kaifeng (Feng et al., 2007) and Changping, Beijing (Xue et al. in prep; see paragraph “Simulation modeling”). Next, this data file was adapted to northern and southern climatic regions within the YRB/NCP by changing the crop growth durations to fit the cropping seasons and cropping patterns. Thus, two “model aerobic rice crops” were created that were both based on HD297 but had different durations. Next, we collected daily weather data of 50 years between 1951 and 2000, from 69 stations in the 5 provinces of our study. We compiled soil information for the area covered by the representative weather stations. The required soil hydrological properties to run the SAWAH water balance model of ORYA2000 were either directly obtained from published data or estimated using pedotransfer functions on available secondary data (texture, soil organic matter content, bulk density). Next, ORYZA2000 was run for each year of each weather station using the representative soil data. We run two scenarios: a potential production situation and a rainfed production situation. In the potential situation, the soil water content in the root zone was kept continuously at field capacity, and we computed "potential aerobic rice yield" and crop water requirements by seasonal evapotranspiration. The difference between crop water requirements and seasonal cumulative rainfall was interpreted as net irrigation demand (or water deficit). In the rainfed scenario, we computed rainfed yields with a groundwater table at 1.9 m depth. We computed the 50-year averages of all simulated variables at each station, and used GIS interpolation techniques to extrapolate the station values to their surroundings (based on the approach of "simulate first, average and interpolate after"). So far, we did not formally include topographic features such as mountains and nearness to the ocean in our interpolation, but selected the interpolation technique that produced maps that visually corresponded best with such features. The results are shown in Figures Figures 6.5.3a-e.

Potential yield in the central part of the YRB are 6-8 t ha^{-1}, which is 0-2 t ha^{-1} higher than the maximum yield recorded in any of our field experiments. However, in our field experiments, we never maintained soil water conditions at field capacity. The potential yields merely indicate the level that could be reached with no stress or water shortages whatsoever. Under farmer conditions, more realistic "attainable yields" (Van Ittersum and Rabbinge, 1997) are defined which usually approach 80% of the yield potential, which would translate into 4.8-6.4 t ha^{-1} in the central YRB. Rainfed yields in the central YRB are also 6-8 t ha^{-1}, indicating that aerobic rice could potentially be grown without irrigation. The categories in our yield maps mask the fact that the rainfed yield are in the lower ranges of each category compared with the potential yields. Most of the area has an average seasonal rainfall of 450-510 mm and a water deficit of only 0-220 mm, which had little impact of yields. It should be noted, however, that in our simulations, we started crop growth with a soil profile down to 1.9 m at field capacity (contributing to crop water requirements by uprise; Bouman et al., 2007), which in reality may not be the case if a winter crop is grown (that has exhausted the soil from water). On average, we can conclude that aerobic rice can be grown under conditions of purely rainfed to about 220 mm of supplementary irrigation (which would practically translate into 3 gifts of 70 mm). This compares well with actual practices of farmers who grow aerobic rice (see below). In dry years, of course, irrigation requirements are higher than in our simulated 50-year average values.

Figure 6.5.3a. Potential aerobic rice yield (t ha^{-1}).

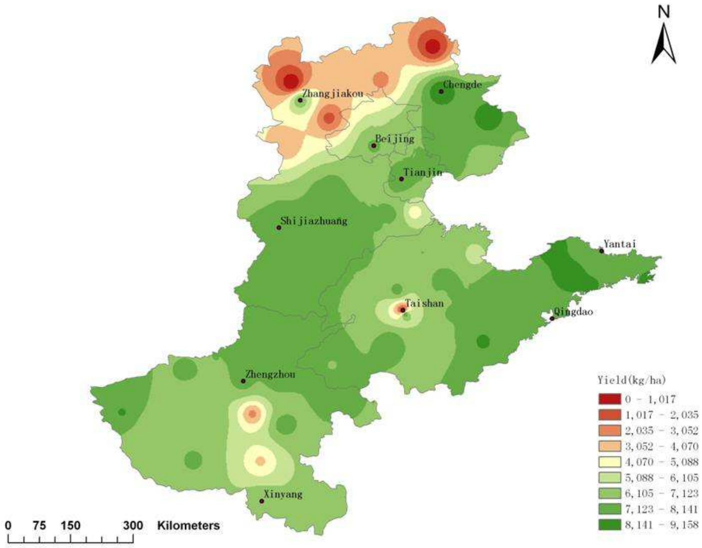


Figure 6.5.3b. Average rainfed aerobic rice yield (t ha^{-1}) with groundwater at 1.9 m.

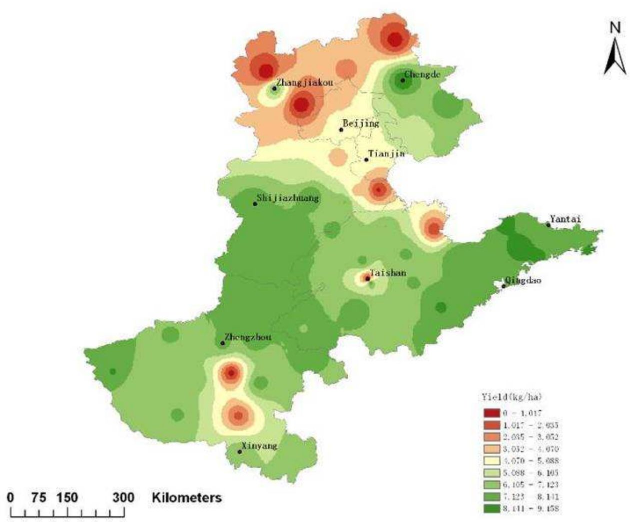


Figure 6.5.3c. Crop water requirement (mm) by evapotranspiration

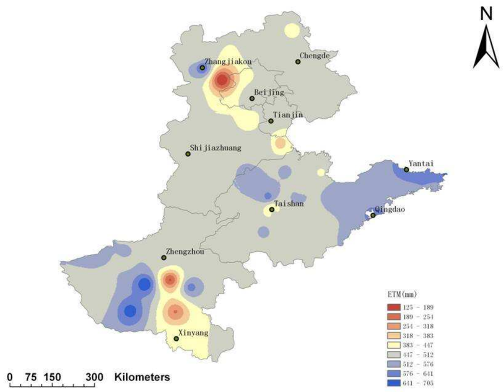


Figure 6.5.3d. Seasonal rainfall (mm)

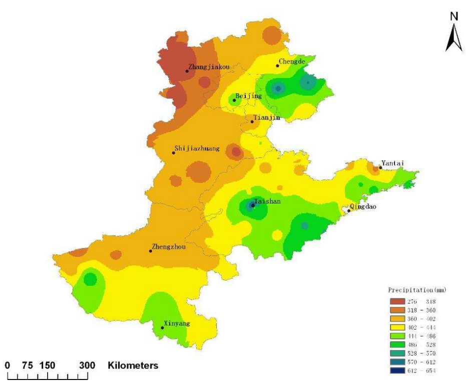
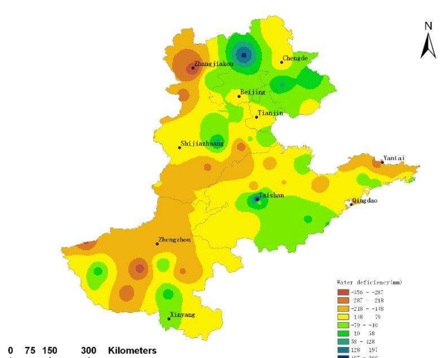


Figure 6.5.3e. Crop water deficit: crop water requirements minus rainfall (mm)



6.5.4. Farmers’ practices

We used data collected in farmers’ fields in Kaifeng before our CPWF project started to complete the supplement the theoretical analysis of target domain presented above (more details by Bouman et al., 2007). In 2002 and 2003, a number of farmers grew aerobic rice and we monitored their yield, water input, and groundwater table depth throughout the growing season. Yield was obtained by interview as whole field yield and includes post-harvest losses from harvest to delivery to the miller as air-dry rough rice. All farmers used only shallow tubewells for irrigation and irrigation water input was computed from measured time of pump operation times the calibrated flow rate of the pump. Rainfall was taken from Hubei experiment station. In 2005, in our CPWF project, we interviewed farmers who had adopted aerobic rice about their yields and harvested areas.

The groundwater table depths observed in farmers’ fields are given in Figure 6.5.4 and demonstrate the variability from shallow to deep (more than 2 m) that can occur in the same area.

The yield and water use are given in Table 6.5.3. Yields were lower in 2003 than in 2002 because of heavy rains during flowering in 2003, which resulted in increased spikelet sterility (the same rainfall that caused the groundwater tables to sharply rise, Figure 6.5.4). Most farmers applied three irrigations in 2002, and, because of more rainfall, only two in 2003. Irrigations were usually given to promote germination after sowing, and between tillering and flowering when there was not enough rainfall. There was no relationship between yield and irrigation water input, nor between yield and groundwater depth.

The yields obtained by farmers in 2005 are given in Figure 6.5.5. Out of 36, five farmers harvested no yield at all (fields were abandoned), and six farmers had yields between 5000 and 5500 kg ha^{-1}. Excluding the abandoned fields, the average yield was 3380 kg ha^{-1} and including the abandoned fields, it was 2900 kg ha^{-1}.

Figure 6.5.4. Measured groundwater depth in aerobic rice fields of farmer A (☐), B (◇), C (☐), G (Δ), and H (*) in 2002 (a), and of farmer V (☐), W (◇), X (☐), and Y (Δ) in 2003. Groundwater depths at fields of other farmers listed in Table 6.5.3 were not measured.

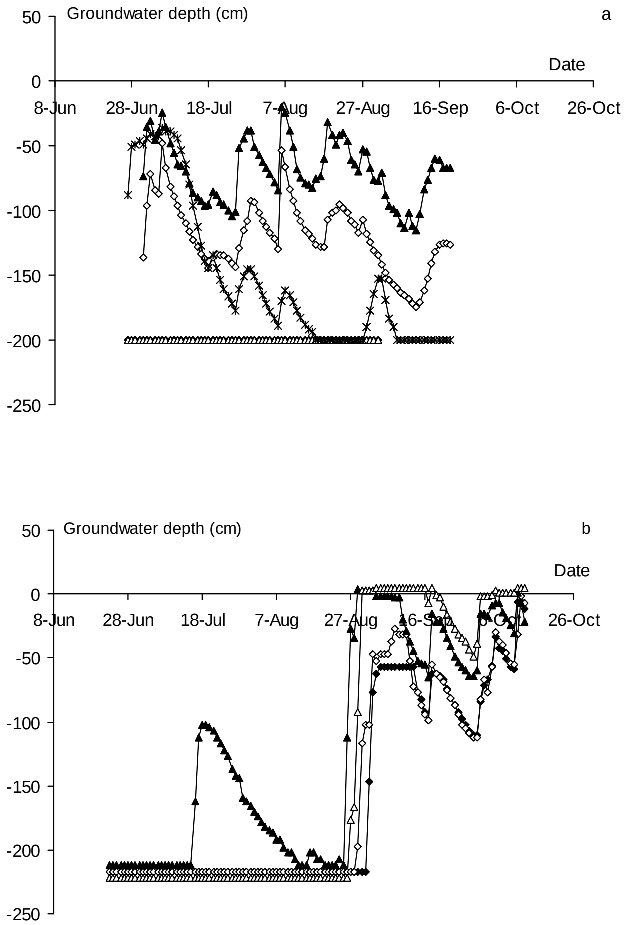


Figure 6.5.5. Frequency distribution of aerobic rice yields by 36 farmers in 2005.

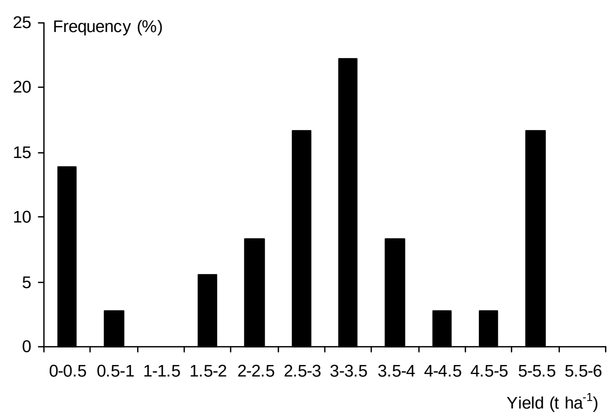


Table 6.5.3. Performance of aerobic rice farmers in terms of yield and water use, Kaifeng, 2002-2003.

Farmer label	A	B	C	D	E	F	G	Mean
2002								
Field size (ha)	0.17	0.11	0.13	0.07	0.07	0.04	0.21	0.12
Yield (kg ha^{-1})	3800	4400	3800	5100	5500	4700	3400	4300
Irrigation (mm)	225	225	80	231	230	300	225	217
Rainfall (mm)	337	337	337	337	337	337	337	337
Total water input (mm)	562	562	417	568	566	637	562	553
2003								
Farmer	U	V	W	X	Y	Z		Mean
Field size (ha)	0.10	0.16	0.06	0.11	0.11	0.13		0.11
Yield (kg ha^{-1})	1200	3825	2400	3750	3608	3038		2970
Irrigation (mm)	156	159	145	169	146	162		156
Rainfall (mm)	674	674	674	674	674	674		674
Total water input (mm)	830	833	818	842	820	836		830

We also synthesized initial socio-economic survey data among farmers in 2002-2003 before our CPWF project started, and did a larger survey in 2005. Beside aerobic rice, the survey included other crops such as lowland rice and upland crops (maize, soybean, cotton, etc). The purpose was a general comparison among alternative crops available to farmers. In 2001-2003, we surveyed a small number of farmers in different sites (Table 6.5.4, Table 6.5.5). In total, 24 aerobic rice fields were included, 20 lowland rice fields, and 21 upland cropped fields. In 2005, we surveyed about 60 households in Kaifeng, Henan, and Fengtai, Anhui, counties. The surveys were accompanied by focus-group discussions to get farmers' opinions on adoption of aerobic rice.

Table 6.5.4. Location and year of aerobic rice surveys, China, 2001-2003.

County	Village	Year
Beijing	Changle, Hanjiachuan	2001
Yingshang	Gaogu, Tulou	2001
Fengtai	Guanzhuang, Dacheng, Zhaixi	2002-2003
Kaifeng	Mengtang, Panlou, Shangzai, Shunji, Xilong	2002-2003

Table 6.5.5. Number of crops (fields/farms) included in the aerobic rice surveys, China, 2001-2003.

Year	Crop	Number of fields
2001	Aerobic rice	4
	Lowland rice	4
2002	Aerobic rice	11
	Lowland rice	11
	Cotton	3
	Maize	3
	Sesame	2
	Soybean	1
2003	Aerobic rice	9
	Lowland rice	5
	Cotton	4
	Maize	6
	Soybean	2

In 2001-2003, returns over paid-out costs to aerobic rice varied from 234 to 591 \$ ha^{-1} (Table 6.5.6). Usually, this was lower than for upland crops. Labor use was about the same level as for maize and soybean, but much lower than for cotton.

Table 6.5.6. Results of aerobic rice surveys, China, 2001-2003.

Costs and Returns in Producing Aerobic Rice and Other Crops in Selected Villages of China, 2001-2003

ITEMS	Aerobic rice	Aerobic rice	Cotton	Maize	Soybean	Aerobic rice	Cotton	Maize	Soybean
	2001	2002				2003			
Production Value	**932**	**662**	**1,843**	**933**	**289**	**554**	**837**	**644**	**341**
Yield (Kg/Ha)	5.6	4.0	3.4	7.5	1.1	3.2	1.2	4.3	1.2
Price (US$)	0.17	0.16	0.55	0.13	0.28	0.18	0.72	0.15	0.28
Total Costs	**420**	**447**	**746**	**284**	**373**	**486**	**674**	**284**	**154**
Chemical Input Costs[1]	221	171	109	111	159	228	168	147	43
Hired Labor Cost (US$/Ha)	0	17	0	0	0	4	0	0	0
Imputed Labor Cost (US$/Ha)	79	183	626	156	168	167	492	116	100
Other Costs[2]	120	75	11	17	46	88	15	22	10
Gross Margin	**512**	**215**	**1,096**	**649**	**(85)**	**67**	**163**	**360**	**187**
Returns Over Paid-out Costs	**591**	**398**	**1,722**	**805**	**84**	**234**	**655**	**475**	**287**

[1] *Chemical Inputs include seeds, fertilizer, pesticide, and weedicide.*

[2] *Other costs also include machine rental and fuel/oil costs.*

In 2005, net returns over costs (including own labor use) to aerobic rice was 326 $ ha^{-1} (Table 6.5.7). This was higher than for maize and soybean, a bit lower than for lowland rice, and much lower than for the cash crops peanut and cotton. Labor use was higher than for soybean, about the same level as for maize and peanut, and lower than for lowland rice.

Overall, we conclude that aerobic rice can be a financially attractive crop, but that profits need to increase to make it more competitive. In focus-group discussions, farmers mentioned that 6 t ha^{-1} is an ideal yield target, while most of the surveyed farmers have yields of 3-4 t ha^{-1}. Aerobic rice uses much less irrigation water (156-217 mm) than lowland rice (1300-1500 mm; Wang Huaqi et al., 2002; Feng et al., 2007), and can well be grown in areas where water shortage excludes the growing of lowland rice. When sufficient water is available, farmers should grow lowland rice instead of aerobic rice as yields and profits are higher. The range of irrigation water application by farmers supports the results of our modeling and GIS study (see above). Farmers mentioned the following reasons for adopting aerobic rice: they want to grow rice when water is insufficient (for lowland rice), ease of establishment, less labor use (compared with lowland rice), good eating quality. Negative views included: low yields, difficult to control weeds, and insufficient extension support. One special positive characteristic of aerobic rice is that it can stand flooding in situations where all other upland crops would suffer or even get completely wiped out. In the peak towards end of summer time, the Yellow River and its tributaries often overflow and cause flooding for a few days to weeks. Under these conditions, aerobic rice still survives and can produce a harvestable yield.

Table 6.5.7. Results of aerobic rice surveys, China, 2005.

Comparative profitability of rice production and other crops in Kaifeng Henan and Fengtai Anhui, China 2005

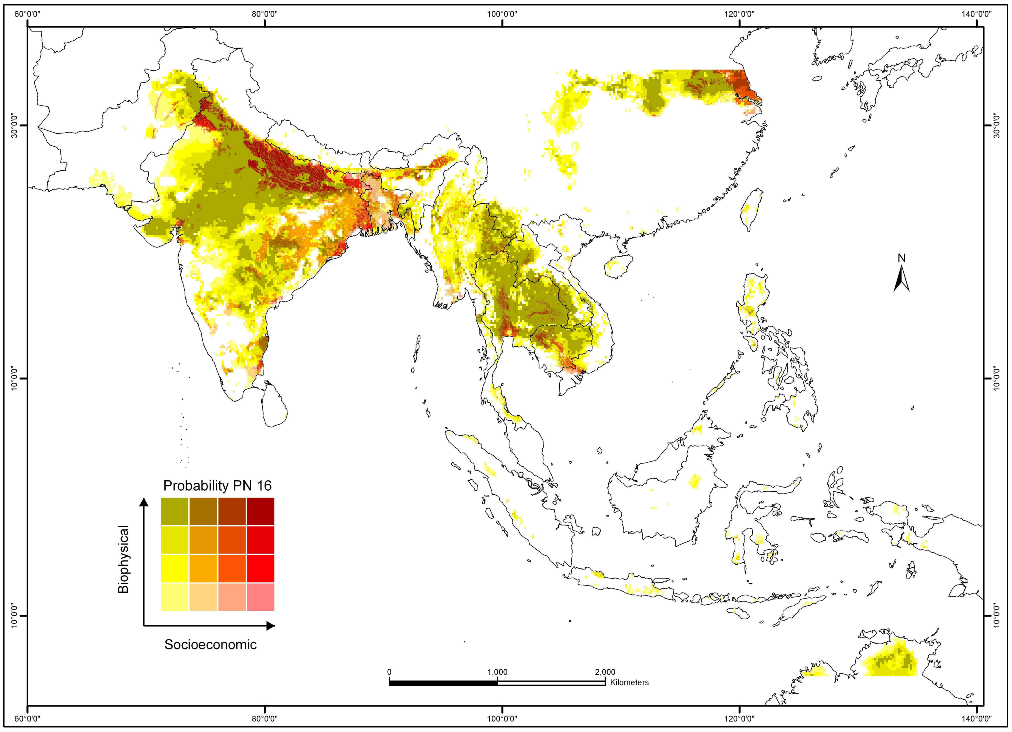
CROPS	Aerobic Rice	Lowland Rice	CORN	SOYBEAN	PEANUT	COTTON
n	59	16	101	43	7	10
Yield	4.18	5.76	4.76	0.25	0.30	1.09
Gross return	967.19	1,316.14	708.98	423.45	1,315.44	1,249.33
Cost of Production						
Material inputs	356.61	413.74	182.40	177.95	317.81	202.25
Fertilizer cost	137.02	178.13	104.61	65.19	111.88	52.36
Insecticide cost	18.02	27.09	11.49	7.01	6.45	28.40
Herbicide cost	19.77	5.76	-	-	-	-
Seed cost	88.02	63.20	34.23	74.52	161.40	107.87
Power cost	54.67	75.96	19.12	28.08	32.20	13.19
Irrigation Cost	16.31	34.46	-	-	-	-
Other Cost	22.79	29.14	12.95	3.15	5.86	0.43
Labor cost	284.86	460.21	225.43	111.98	282.43	395.35
Hired labor	2.89	48.42	-	-	-	-
Imputed family labor cost	281.97	411.78	225.43	111.98	282.43	395.35
Total Paid out cost	359.50	462.17	182.40	177.95	317.81	202.25
Total cost	641.47	873.95	407.83	289.93	600.23	597.60
Return over paid out costs	607.69	853.97	526.58	245.50	997.64	1,047.09
Net return	325.73	442.18	301.15	133.52	715.21	651.73

6.5.5. Extrapolation domains

We collaborated with the Impact Project of the CPWF to develop extrapolation domains to explore the impact potential of aerobic rice. Although this work is still in progress, we report summary results to date (taken from Rubiano et al., 2007). Potential extrapolation domain areas for aerobic rice were calculated using Homologue and Weights of Evidence modelling that look for similar agro-ecological and socio-economic conditions to those found in project pilot sites. The analysis shows that the highest probability areas are all in Asia (Figure 6.5.6). In India, the extrapolation domain is largely centred on the rice-wheat systems in the Indo-Gangetic basin. In Thailand and Burma the areas are centred on rainfed lowland areas. The analysis found large areas that are suitable climatically in Africa in Zimbabwe, Mozambique, Madagascar, Burkina Faso and Nigeria, and in Latin America, in Brazil, Bolivia and Venezuela.

The pan-tropical perspective of the extrapolation domain analysis is both its strength and weakness. The extrapolation domain analysis is restricted to using publicly available pan-tropical databases that necessarily restrict the socio-economic variables that can be modelled. The extrapolation domain areas and the quantification of potential impacts presented in this paper are important not in absolute terms, but in the trends they show. Extrapolation domain and scenario analysis are useful not for predicting what will happen, but rather exploring what could happen.

Figure 6.5.6. Extrapolation domains for STAR aerobic rice in tropics in Asia



6.5.6. Conclusion

Aerobic rice holds promise for farmers in water-short irrigated or rainfed environments where water availability at the farm level is too low, or where water is too expensive, to grow flooded lowland rice. When the percolation losses in flooded rice are 3.5 mm d^{-1} or higher, aerobic systems with flash-flood irrigation will require less water, and if the percolation losses are 0.5 mm d^{-1} or lower, only aerobic systems with sprinkler irrigation require less water. In northern China, the target areas are where water availability (rainfall with or without supplementary irrigation) is 400-900 mm during the cropping season. Suitable varieties here are HD297 and HD502 (among others). In the central part of the Yellow River Basin (Kaifeng area), and in most of the North China Plain, attainable yields of 5-6 t ha^{-1} are possible with 0-220 mm irrigation application (in average rainfall years; groundwater 2 m deep or less). In these regions, farmers who currently try out aerobic rice attain usually 3-4 t ha^{-1}, with 150-220 mm supplementary irrigation (though some farmers get up to 5.5 t ha^{-1}). With these yields, financial returns to aerobic rice can be more or less than to upland crops (maize, soybean), depending on relative market prices (that fluctuate among years). Yields need to go up to 6 t ha^{-1} to make aerobic rice more competitive. Reasons for adoption are: having own rice on the farm, ease of establishment and less labor needs (compared with lowland rice), good eating quality. Negative views are: low yields, difficult to control weeds, insufficient extension support, difficult to market. Aerobic rice is unique in its characteristics to withstand both flooding and dry soil conditions, which make it an ideal crop for areas prone to surface flooding where other crops would suffer or fail. Extrapolation domain construction and scenario analysis suggest that aerobic rice can have large impacts in India and countries in the lower parts of the Mekong Basin.

7. INTERNATIONAL PUBLIC GOODS

The main international public good (IPG) produced by the project is the concept of aerobic rice: a new rice production system in which specially developed, input-response rice varieties with "aerobic adaptation" are grown in well-drained, nonpuddled, and nonsaturated soils without ponded water. Aerobic rice is aimed at water-short irrigated or rainfed environments where water availability is insufficient to grow flood-based lowland rice. Although our project did not actually breed new rice varieties suitable for aerobic production systems, it did identify suitable and released varieties

- Northern China: HD277, HD297, HD502
- India: Pusa Rice Hybrid 10, Proagro6111 (hybrid), Pusa834
- Philippines: "Apo" (PSBRc9), UPLRI5, PsBRc80

Released varieties are available without restrictions through private seed companies or national public seed distribution channels (including universities and institutes). For Thailand and Laos, only suitable genotypes (breeding "lines") were identified for further breeding (see paragraph "Aerobic rice varieties identified).

Our project produced initial management options and guidelines with respect to crop establishment, irrigation, and fertilization. Aerobic rice is basically managed like a wheat or a maize crop. The usual establishment method is dry direct seeding. Before sowing, the land should be dry prepared by ploughing and harrowing to obtain a smooth seed bed. Seeds should be dry seeded at 1-2 cm depth in heavy (clayey) soils and 2-3 cm depth in light-textured (loamy) soils. Optimum seeding rates still need to be established but are probably in the 70-90 kg ha^{-1} range. In experiments so far, row spacings between 25 and 35 cm gave similar yields. The sowing of the seeds can be done manually (e.g., dibbling the seeds in slits opened by a stick or a tooth harrow) or using direct seeding machinery. An alternative establishment method is transplanting, where seedlings are transplanted into wet soil that is kept around saturation for a few days to ease transplanting shock. Subsequently the fields dry out to field capacity and beyond. This method of crop establishment can only be done in clay soils with good water-holding capacity. An aerobic rice crop attaining 4-6 t ha^{-1} yields obtains many of its required nutrients from the soil. But this "indigenous supply" of nutrients is typically not sufficient to meet all the nutrient needs, and fertilizers will need to be applied. Site-specific knowledge about the indigenous nutrients supply is the starting point for formulating fertilizer recommendations. The site-specific nutrient management (SSNM) approach (www.irri.org/irric/ssnm) can be used to determine the need for supplemental nutrients in the form of fertilizers and the optimal management of fertilizers. A useful tool to assist in the application of nitrogen (N) fertilizer is the Leaf Color Chart (LCC; part of the SSNM approach). In the absence of trained extension personnel in SSNM and LCC, an amount of 70-90 kg N ha^{-1} could be a useful starting point (to be subsequently optimized). Instead of basal application of the first N split, the first application can best be applied 10-12 days after emergence to minimize N losses by leaching (the emerging seedling can't take up N so fast, so it will easily leach out). Moreover, basal application of N also promotes early weed growth. Second and third split applications of N may be given around active tillering and panicle initiation, respectively. Dry, aerobic, soil can reduce the indigenous supply of phosphorus (P), hence the application of fertilizer P can be more critical for aerobic rice than for conventional flooded lowland rice. On acid soils, aerobic rice will likely be less prone to zinc deficiency than flooded lowland rice; but on high pH soils with calcium carbonate, the reverse may be true. If the crop is grown in a dry season, a light irrigation application (say 30 mm) should be given after sowing to promote emergence. Subsequent irrigation applications depend on the rainfall pattern, the depth of groundwater, and on the availability and/or cost of irrigation water. Irrigation can be applied by any means as used for upland crops: flash flood, furrow, or sprinkler. Rice that is not permanently flooded tends to have more weed growth and a broader weed spectrum than rice that is permanently flooded. To control weeds, the use of pre- or post-emergence herbicides is recommended when the weed pressure is high, plus additional manual or mechanical (inter-row cultivation) weeding in the early phases of crop growth.

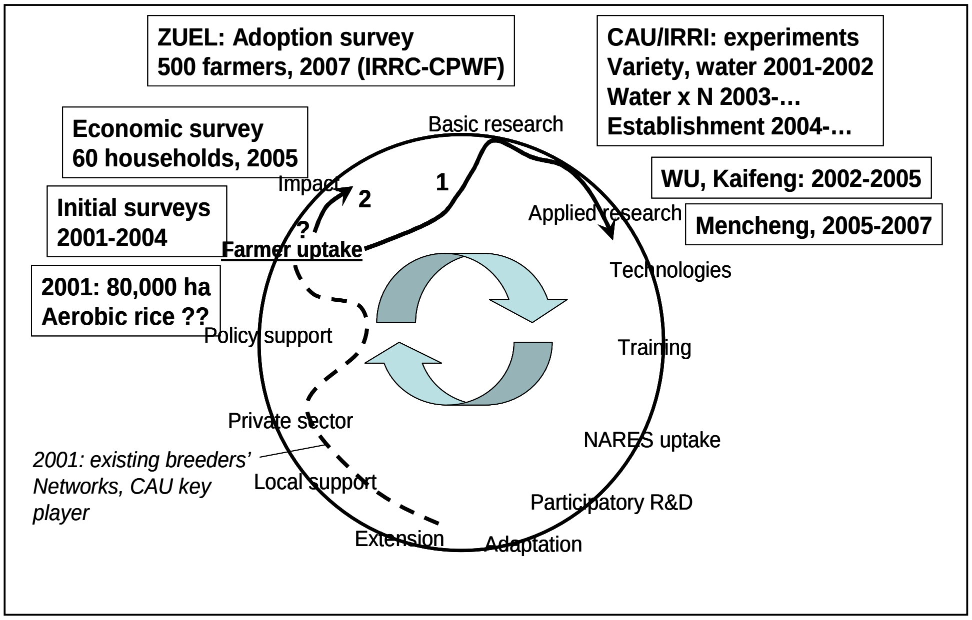
The methods we used were pot experiments, field experiments, simulation modeling, GIS, and socio-economic household surveys. The crop growth simulation model was evaluated for aerobic rice variety HD295 and aerobic field conditions, and can be freely obtained from IRRI (http//www.knowledgebank.irri.org/oryza2000/). Experiment protocols and survey forms used can be obtained from the project partners. No new research technologies or methodologies were developed in this project. Experimental data are reported in this report and in national and international publications.

8. OUTCOMES (PARTNER CHANGE)

Before this CPWF project, IRRI and a few partners in China, India, and the Philippines initiated research and development activities on aerobic rice in 2001, coordinated through the Water Workgroup of the Irrigated Rice Research Consortium (IRRC). Until 2004, activities were modest, operating on small budgets. The CPWF allowed us to increase the scale of our R&D operations considerably and both scale up and out. The number of partners increased, and we opened new sites with new partners in Laos and Thailand. The biggest partnership changes occurred in China and the Philippines. Although the seeds for change were sown from 2001 onward, it was the CPWF that was instrumental in bringing these changes to fruition.

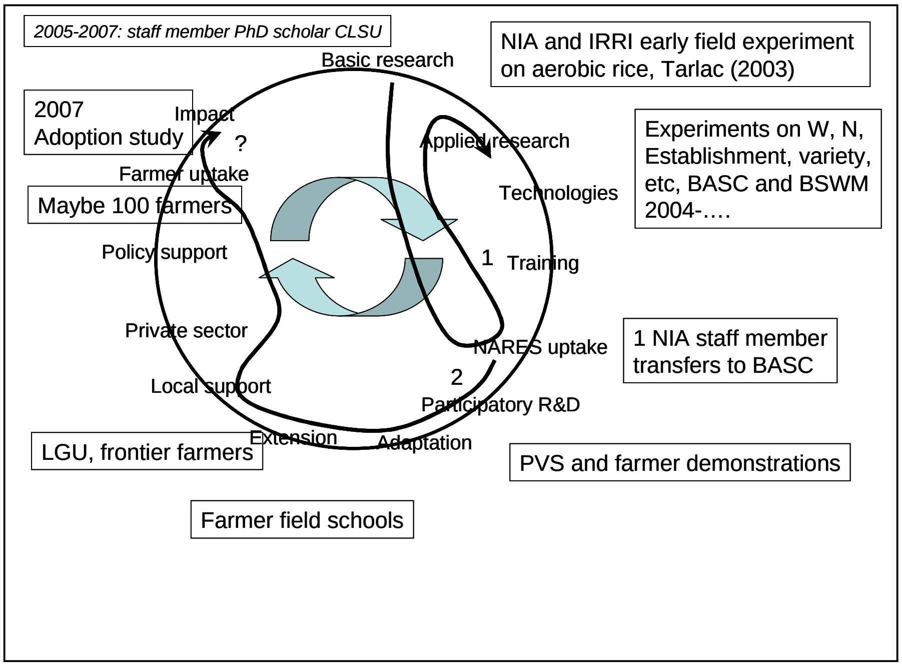
In China, breeders have been developing aerobic rice varieties since the early nineteen eighties, and extending their varieties through upland rice networks and channels. Without much research on the management and performance of these varieties, breeders interacted directly with extension networks and farmers. Through the CPWF, we were able to add a research dimension, especially on crop physiology, plant nutrition, agro-hydrology, modeling, and crop management in general, which was not present before. Initially primarily the domain of breeders, now the aerobic rice effort at China Agricultural University is led by a multi-disciplinary team from various departments. The activities of this team, and the status of working in an international partnership, have attracted the attention of university leaders and increased the support for aerobic rice research. Members of the team were able to secure additional national funds to support their aerobic rice research. Moreover, the exposure to the concept of impact-pathways during the Zengzhou workshop organized by the CPWF in June 2007, increased the awareness of the team members of "thinking beyond research" (though no tangible results of this change can yet be reported). Besides working in well-controlled field experiments, some of the team members initiated on-farm research and participated in socio-economic surveys among farmers in China. The need for studying impact and adoption has become evident and team members also participated as resource persons in an externally commissioned impact and adoption study. The "changes in partner" may be illustrated among a circular Impact-Pathway (Figure 8.1). In 2001, CAU breeders operated on the left side of the circle, working on extension and farmer-uptake of aerobic rice through private sector (seed companies) partnership and local government support. However, there was no research component and questions on how to best manage the new aerobic rice varieties in a sustainable and profitable way were left unanswered. Mainly through the CPWF project, a basic and applied research component was added to answer these questions (arrow 1; started in 2001, but on a small scale). Also, there was little knowledge on the actual extent of farmer uptake of aerobic rice, reasons for adoption, and impacts of adoption. Through the CPWF, awareness of the need for insight into these processes led to the first impact assessments and adoption studies of aerobic rice in northern China (arrow 2). In summary, the "partner change" was the addition of a scientific research base on crop management and impact/adoption to the existing breeding-extension network, thereby enriching the impact-pathway circle.

Figure 8.1. Partnership change (CAU), China 2001-2007.



In the Philippines, the network of partners expanded rapidly with the CPWF. Again, the seeds of change were sown from 2001 onward, but the CPWF allowed us to scale out in terms of partners. Originally, two Philippine national partners were included as official project partners: PhilRice, and the National irrigation Administration in Tarlac. Through the success and visibility of their activities (they organized and attended many national workshops and trainings), more and more R&D partners became interested in aerobic rice. The most prominent are listed as project partners "without CPWF funds": Bulacan Agricultural State College (BASC), Central Luzon State University (CLSU), and the National Soil and Water Resources Research and Development Center - Bureau of Soil and Water Management (BSWM). These partners consider themselves full member of the aerobic rice project and fully participated in project planning and discussion meetings and workshops. These partners picked up different components of the Impact-pathway circle according to their own mandates and interests, ranging from research to teaching, training, and extension. CLSU, through its Water Resources Management Bureau, introduced aerobic rice in trainings on water management and embarked on research on sprinkler irrigation of aerobic rice. BASC and BSWM jointly initiated a range of applied research activities and started extending the aerobic rice to farmers in the area. Each year, trainings were provided and farmer field schools organized. The case of BASC-BSWM is illustrated again with the Impact-pathway circle (Figure 8.2). In 2001-2003, NIA collaborated with IRRI on aerobic rice field experiments in Tarlac. In 2003, one NIA staff member transferred to BASC and motivated the college to develop an aerobic rice RD&E program to serve their students and farmers in the province (arrow 1). Applied research on crop management and variety selection was started in 2004 and continues up to today. Also, farmer training, demonstrations, and field schools in the neighboring areas were initiated and support mobilized through Local Government Units (LGU) and village leaders. Within a few years, a rather complete set of activities along the Impact-pathway circle has been developed at the local scale (encompassing s few villages, but ambition to scale up and out nationally!). BASC and BSWM were successful in applying for national R&D grants to finance their activities, and it was their participation in high-profile programs such as the IRRC and the CPWF that contributed to that success.

Figure 8.2. Partnership change (BASC-BSWM), Philippines, 2004-2007.



The above examples highlight two "partner changes" of the project All project partners benefited a lot from working in partnerships (both IRRC and CPWF), and the value of interaction at joint planning meetings, trainings, and workshops can not be over-stated. Though we did not systematically document it, we believe that significant "partner changes" along the Impact-pathway have happened over time. Three key lessons we learned are:

1. Let partners take ownership, and give them freedom to modify and adapt concepts and practices.
2. Be flexible in partnership arrangements; follow new initiatives developed by new partners; include new and exciting partners in the project. Unfortunately, this is usually hindered by project arrangements (such as in the CPWF project contracts) in which partners need to be identified beforehand with their roles and responsibilities exactly identified at the start.
3. Create opportunities for new partnerships through training.

9. IMPACTS

9.1. Science

At the time of writing, four international journal papers have been published and seven are submitted or in advanced stage of preparation (see chapter "Publications"). Three international journal papers included parts of our CPWF results, and seventeen national journal papers, book or proceeding chapters are published. Moreover, a large number of posters (>20) have been presented, and oral presentations made at workshops, conferences, and other fora. We organized an international Aerobic Rice workshop in Beijing, October 22-25, 2007, which attracted about 100 participants. All abstracts and papers are available on CDROM. The concept of aerobic rice is getting accepted in scientific research as evidenced by participants with papers to the international Aerobic Rice workshop in Beijing who were not part of our project.

9.2. Capacity building

Twenty-two graduate and undergraduate students were involved in the project, and most of them have completed their theses (see chapter "Publications"). Fourteen students were enrolled at China Agricultural University, three at Central Luzon State University (Philippines), two at the University of the Philippines Los Banos (Philippines), two at Wageningen University (Netherlands), and one at the Universita degli Studi di Firenze (Italy).

Aerobic rice was part of many training courses on water management in rice production systems organized conjunctively by the Water Workgroup of the Irrigated Rice Research Consortium and our CPWF project (we can not separate out the contributions as these were real joint activities). The audiences of these courses were staff from institutes, universities, extension agencies, and irrigation system administrators with a mandate for applied research, water management, or extension. The trainings did not extent to our own project partners as they received "on the job training". These trainings were part of our outreach activities on aerobic rice. Table 9.2.1 lists the most relevant course where aerobic rice was a major component, with number of participants. The majority of the courses was organized in the Philippines, but there were also trainings in Bangladesh (IGP), Vietnam (Mekong, Red River), and Myanmar (Irrawady). In total, 1589 professionals received training on aerobic rice during the lifetime of our CPWF project.

Table 9.2.1. Water management trainings with a significant component of aerobic rice, jointly organized by the CPWF project and the IRRC, 2004-2007.

	Course Title	Place/Country	Date offered	Partici-pants
1	Integrated water management in rice production -- technology transfer for water savings	Los Banos, Philippines	4-8 October 2004	34

2	Integrated water management in rice production -- technology transfer for water savings	Muñoz, Philippines	8-12 November 2004	34
3	Integrated water management in rice production -- technology transfer for water savings	Tuguegarao, Philippines	11-13 November 2004	38
4	Integrated water management in rice production -- technology transfer for water savings	Muñoz, Philippines	8-10 December 2004	33
5	Integrated water management in rice production -- technology transfer for water savings	Batac, Philippines	15-17 March 2005	40
6	Integrated water management in rice production -- technology transfer for water savings	Tarlac, Philippines	15-17 March 2005	40
7	Training on Water Saving Technologies	Pilar, Bohol, Philippines	26-27 April 2005	35
8	Training on Water Saving Technologies	Barangay Patong, Philippines	10-13 May 2005	35
9	Training on Integrated Field Water Management	Bagan, Myanmar	5-7 October 2005	40
10	Training on Integrated Field Water Management	Bohol, Philippines	19-21 December 2005	30?
11	Training on Water Saving Technologies	Bohol, Philippines	Feb 2-17, 2006	500
12	IRRI Rice Production Training Course	Los Banos, Philippines	30-Mar	20
13	Training on water saving technologies and implementation of Integrated Crop Management in Vietnam	Nan Dinh and Habac, Vietnam	March 18-26, 2006	30

14	Training on Water Saving Technologies	Manila, Philippines	March 2-4, 2006	
15	Training on component technologies…	Bohol, Philippines	July 5-6, 2006	24
16	Training on Water Saving Technologies	Cebu, Philippines	18-23 July 2006	60
17	Training on Water Saving Technologies	Cebu, Philippines	26-27 Sept 2006	40
18	Integrated field water management	Negros, Philippines	28-29 Sep 2006	40
19	Science and Technology updates Rice production	Muñoz, Philippines	26-Jan-07	50
20	Science and Technology updates Rice production	Muñoz, Philippines	08-Feb-07	50
21	Lecture: Water savings at NIA Facilitators training	Quezon City, Philippines	09-Feb-07	50
22	Lecture: Water savings at NIA Facilitators training	Quezon City, Philippines	16-Feb-07	50
23	Training workshop on water-saving technologies for rice production in rainfed areas	Bulacan, Philippines	12-Apr-07	30
24	Water Management training course	Hanoi, Vietnam	03-May-07	50
25	Technology forum	Alaminos, Pangsinan, Philippines	may 10-11, 2007	35
26	Water Management seminar	Los Banos, Philippines	17-May-07	25
27	Integrated field water management	Maasin, Leyte, Philippines	June 21-22, 2007	40
28	Integrated field water management	Libmanan, Cam Sur, Philippines	August 20-21, 2007	36

29	Integrated field water management	Gazipur, Bangladesh	August 26-28, 2007	40
30	Water Management seminar	IRRI, Los Banos	17-May-07	25
31	Water Management training course	FCRI, Hanoi, Vietnam	Dec 18 2007	50
32	Water Management training course	NOMAFSI, Phuc Ho, Vietnam	Dec 20 2007	15

Our national and local project partners organized many farmer trainings through farmer school days and visits to demonstration sites. A typical farmer school day/demonstration day would involve 50-100 farmers for the duration of one day. We did not keep track of all farmer school days/demonstrations organized during the project as many were local initiatives that went unrecorded. Table 9.2.2 provides a rough estimate of yearly outreach events and number of farmers reached for each partner country. Over the 3.5 year span of our project, we estimate that we reached 1875-3750 farmers with information about aerobic rice.

Table 9.2.2. Estimated yearly number of outreach events to farmers on aerobic rice, and estimated number of farmers reached.

Country	Area (province, county)	Participants per site	Total number
China	Fengtai, Mencheng, Kaifeng, Funan, Fengyan	50-100	250-500
India	Bulandshahar	50-100	50-100
Thailand	Scattered villages in NE Thailand	50-100	50-100
Laos	Three breeding trial sites	25-50	75-150
Philippines	Bulacan, Nueva Ezija, Tarlac, Bataac	50-100	200-400
			625-1250

9.3. Community impacts

We studied the socio-economics of aerobic rice cropping in a case study in China and the results are reported in the paragraph "Farmers' practice". The major impact of the aerobic rice technology is that it offers farmers the choice to grow rice when water is too scarce to grow lowland rice. It allows farmers to diversify their cropping system which will augment resilience and increase overall sustainability. Adoption will (among others) depend on relative market prices the different crops available to farmers are expected to fetch in a particular year, the degree of water scarcity, availability of quality seeds and extension support, and – last but not least – farmers' preference to grow their own rice for self sufficiency rather than depending on markets. Aerobic rice is not a system that increases yields and profitability of rice per se, and therefore is not expected to increase farm income (again depending on the price of relative crop products). However, it can contribute to farm household food security and can have impacts on the price of rice if large-scale adoption takes place (see paragraph "Global impacts").

We commissioned an external impact/adoption study of aerobic rice in northern China and results will be made available to the CPWF (and general public) early 2008.

9.4. Global impacts

We collaborated with the Impact Project of the CPWF to develop scenario analyses to explore the impact potential of aerobic rice. Although this work is still in progress, we include summary results to date as reported by Rubiano et al., (2007), with the scenario analyses done by IFPRI (Claudia Ringler, Tingju Zhu). The scenario analyses were carried out using the IMPACT-WATER model to explore the potential impacts of the adoption of aerobic rice over a 20-year period. The International Model for Policy analysis of Agricultural Commodities and Trade (IMPACT) was created in the 1990s to address a lack of a long-term vision and consensus about the actions that are necessary to feed the world in the future, reduce poverty, and protect the natural resource base. IMPACT covers 32 commodities (which account for virtually all of world food production and consumption), including all cereals, soybeans, roots and tubers, meats, milk, eggs, oils, meals, vegetables, fruits, sugar and sweeteners, and fish in a partial equilibrium framework. It is specified as a set of 43 country and regional-level supply and demand equations, which are linked through trade. IMPACT-WATER is an extension of the IMPACT model by a Water Simulation Model (WSM) for projections of water supply and demand. Water supply and demand, and food production are assessed at the river basin scale, and food production is summed to the national level, where food demand and trade are modelled. Currently, IMPACT-WATER has aggregated spatial scales of to a total of 126 river basins, 115 countries and regions, and 281 so called "food-producing units" (FPUs).

The run used the extrapolation domain areas reported in paragraph "Extrapolation domain" that corresponded to a 70% or greater chance of finding similar conditions to the pilot sites of our project. Four scenarios were run:

1. Rainfed-only adoption, no climate change
2. Rainfed and irrigated adoption, no climate change
3. Rainfed-only adoption, climate change
4. Rainfed and irrigated adoption, no climate change

The following assumptions were made on adoption:

Rainfed-only adoption assumes:

a) The adoption of aerobic rice in rainfed areas starts from 2005 if the FPU includes pilot sites or 2010 otherwise. Adoption continues for 20 years until the area grown to aerobic rice equals the potential extrapolation domain in that FPU.

b) There is no adoption of aerobic rice in irrigated areas

c) Adoption of aerobic rice is assumed to increase rice yield by 50%, and the crop ET requirement over the whole growing period are reduced to 450 mm for FPUs in temperate climate zone, 900 mm in subtropical climate zone, and 1000 mm in tropical climate zone, on average, varying from year to year according to climate conditions.

Rainfed and irrigated adoption assumes:

a) If the extrapolation domain (ED) area is less than the existing area of rainfed rice, only rainfed rice areas will adopt.

b) If the (ED) area is greater than the rainfed rice area in the FPU, aerobic rice will replace all the rainfed rice and part of the irrigated rice.

c) If the ED area is more than the current rice growing area in a FPU then aerobic rice will be adopted over the whole are and there will be an expansion in the area grown under rainfed rice.

The main results are:

<u>Water savings</u>. Analysis of potential water saving was conducted only for the adoption of aerobic rice in irrigated areas, thus saving is only discussed for rainfed and irrigated adoption scenarios. With climate change, adoption of aerobic rice could lead to a 50% saving in irrigated water in the Yellow River, China, 28% saving in the Mekong, Thailand and about 22% average saving in four FPUs in India. Without climate change, the only real saving in irrigated water adoption will be in China. This is because under normal climatic conditions aerobic rice hardly affects ET, rather water savings come from reduced percolation and seepage, factors that the IMPACT-WATER does not model for. More water is saved under climate change because requirements for irrigated rice increase with higher ET levels in the climate change scenario. Most of the water saving is in the Indo-Gangetic basin.

<u>Rice supply, demand, prices, and levels of malnutrition</u>. Significant replacement of rainfed rice with aerobic rice in the extrapolation domain areas will lead to changes in rice supply, demand, prices, trade, and levels of malnutrition. Adoption of aerobic rice will have a greater positive impact under climate change because climate change will increase water shortages, and adoption of aerobic rice reduces the water requirement for rice production. The impact of aerobic rice on price production will be concentrated in India and Thailand, which contain 44% and 33% of the potential aerobic rice extrapolation domain areas respectively. Climate change will lead to increases in rice prices

over the next 50 years but adoption of aerobic rice will dampen the price increase with and without climate change. Declining rice prices will make food more affordable for the poor. Without climate change, the number of malnourished children declines from 147 million children in 2000 to 77 million children by 2050, mostly in South Asia and Sub-Saharan Africa. With climate change, the decline is only to 81 million children by 2050. Adoption of aerobic rice through enhanced yield and production will reduce malnutrition under both alternative scenarios.

Trade. India is the country with the largest potential expansion for tropical aerobic rice. According to the IMPACT-WATER projections, India is a net rice importer by 2050 with net imports of 15 million metric tons without climate change, and 22 million metric tons with climate change. If rice production in rainfed areas increases as a result of higher aerobic rice yields, then this will help reduce rice imports. Additional production as a result of adoption of aerobic rice will be important under climate change, because IMPACT-WATER predicts that there will be less volume of rice available for trading in 2050 as rice production will be stressed in most developing-country producers.

In summary, the analysis showed that the potential impacts of aerobic rice could be large and beneficial, and will be even more important given temperature and water stress from increased climate variability and climate change. The analysis also showed that most of the impacts would occur in India and Thailand and would include increased yields, production, and area grown to rice, reduced rice prices, and reduced levels of child malnutrition. The IMPACT-WATER model founds that India will be a net importer of rice in 2050. Adoption of aerobic rice would reduce the amount of imports necessary, which could be very important if climate change stresses rice-growing areas in the tropics, as predicted, and reduces the amount of rice available for trade.

The results of the scenario analysis are sensitive to the evapotranspiration (ET) levels chosen for aerobic rice. An earlier run used an ET of 450mm in all extrapolation areas and as a result predicted much higher levels of water saving and yield increase. However, the main water savings from aerobic rice come from reduced seepage and percolation losses, which is not yet factored into the scenario analysis. Hence, the current predictions of water saving and yield increase on an acreage basis are likely to be conservative.

10. PARTNERSHIP ACHIEVEMENTS

None of the reported results, outputs, outcome, or impacts would have been possible without the partnerships established within the project and by the project with "new" partners (not listed as partners in the original project proposal and signed contract). All achievements are a direct result of the CPWF project partnership. Most of the reported results were obtained through activities (experiments, modeling, surveys) by the project partners (Chapter "Results and outcomes); many of the trainings were organized by or through project partners (paragraph "capacity building"); all of the farmer schools, demonstration activities and other farmer-outreach events were organized by the project partners (paragraph "capacity building"). Five universities contributed to graduate and undergraduate training of project scholars. Important other partnership issues are reported in chapter "Outcomes (partner change)".

In the spirit of promoting partnerships of the CPWF, we strengthened existing links and created new ones with other projects, programs, or consortia relevant to the development and dissemination of aerobic rice ("network weaving"). Most importantly:

4. The water Workgroup of the Irrigated Rice Research Consortium (IRRC), that initiated the first (modest) partnership on aerobic rice in 2001. Our CPWF project collaborated with a number of the same partners and build-on and expanded their activities in China, India, and the Philippines.
5. The Consortium for Unfavorable Rice Environments (CURE). We collaborated with this consortium in the rainfed and more unfavorable environments of Laos and Thailand.
6. The ADB-funded project on "Developing and Disseminating Water-Saving Rice Technologies in South Asia". This project has a large component on aerobic rice and we collaborated especially on the issue of soil health and sustainability. There are no common project partners or sites (their sites are in India, Bangladesh, Pakistan, and Nepal).

We shared information (research protocols, ideas, results, outputs, data) as much as possible and conducted many joint project planning and discussion meetings and workshops. In fact, there was no CPWF project planning meeting or workshop that was not combined with one or more of the other project/consortia meetings. The advantages of this collaboration to the development of the aerobic rice technology can hardly be quantified (or overstated!), but all participants considered them of tremendous benefit. The only drawback may be the difficulty in attributing certain activities, results, outcomes, or impacts specifically to any of the partnership members (such as the case of trainings reported in paragraph "Capacity building"). For the overall goal of poverty alleviation and food security, such considerations, however, should not matter.

11. RECOMMENDATIONS

The aerobic rice technology can be considered sufficiently mature for dissemination in the Yellow River Basin (YRB), but not so for most of tropical Asia where more R&D is needed to create sustainable and high-yielding aerobic rice systems. Therefore, our recommendations are made for two regions: the YRB, and "Tropical Asia". The IGP in central India seems to take an intermediate position.

11.1. Policy makers

We recommend that "aerobic rice" be recognized as a special crop type besides the existing categories of "lowland rice and "upland rice". This will facilitate the collection of statistics on adoption and spread of aerobic rice, and will encourage formal extension agencies to address aerobic rice and meet farmers' demands for extension support. In the YRB, local and national governments should strengthen the extension system at all levels. To date, most knowledge on aerobic rice is located within universities and institutes and extension agencies have little knowledge of aerobic rice. In most of tropical Asia, preference should be given to setting up dedicated aerobic rice breeding programs and strengthening the R&D capacity to develop sustainable production systems.

11.2. Extension

In the YRB, the formal extension agencies should be equipped with knowledge on aerobic rice. However, the "informal" extension sector is a powerful agent of change and should be included in the supply of information. We usually found local "technicians", i.e. agricultural shop keepers and informal farmer leaders with some agricultural training, at the basis of adoption of aerobic rice whenever we interviewed farmers.

In most of tropical Asia, care should be taken with the extension of aerobic rice. Although yields of current aerobic varieties can reach up to the same level as in the YRB, they are not as well adapted to aerobic soil conditions and the soil needs to be kept much wetter (using more water) than in the YRB. Moreover, the experiences with "yield collapse" in the Philippines suggest that more R&D effort is needed to develop high-yielding and sustainable systems. In the Philippines, we encountered yield collapse in some farmers' fields (e.g., Tarlac, Nueva Ezija), but we also had experiences of high yields in others with no sign of yield collapse at all (e.g., Bulacan). Where water is scarce, farmers are usually very keen to try aerobic rice and careful guidance by extension agents is warranted. In central India (IGP), lowland rice is often grown on permeable soils with intermittent flooding (because of water scarcity). Here, aerobic rice yields were found to be at par with such lowland rice systems, but using less water. Aerobic rice can be disseminated in such areas, using selected varieties as reported here, as no cases of yield collapse have been reported. In Thailand and Laos (Mekong), more breeding and variety selection needs to take place before aerobic rice can be promoted on a large-scale. Also, improved management practices need first be developed.

11.3. Research

At the international Aerobic Rice workshop (Beijing, 22-25 October 2007), three independent experts presented a detailed list of research recommendations: dr E. Humphreys (CPWF-Theme Leader Crop Water Productivity), dr G. Singleton (IRRC coordinator), and dr A. Dobermann (program leader irrigated environment, IRRI). These recommendations are completely and without editing reproduced in Appendix C. Based on these recommendations and our own experiences, we propose the following major recommendations:

General (both YRB and the Tropics)

1. A better understanding is needed of the factors that influence farmers in adopting/adapting an aerobic rice cropping system. Impact and adoption studies are needed, especially in areas where aerobic rice is currently being adopted such as northern China. Such studies should include both biophysical factors (eg water availability, soil type) and socio-economic factors.
2. Long-term trials such as at IRRI need to be established in a number of target locations to study long-term sustainability and develop sustainable practices. Does yield decline with continuous cropping? Are there any soil-health issues? What are suitable crop rotations? What will be the pest and disease problems in aerobic systems (above ground and below ground)?
3. Make an inventory of "soil health" threats across the potential target domains.

YRB

1. Improve the yield potential. Highest recorded yields in our field experiments were 6 t ha^{-1}, whereas simulation modeling suggests that yields could go up to 8 t ha^{-1}. We need to explore breeding options to increase the panicle (sink) size since the source size of current aerobic rice varieties seems strong enough. Also, we need to further investigate whether yield of current varieties can be increased by improved management, especially that of micro-nutrients such as manganese. There seems to be a lot of scope to improve management, especially related to plant nutrition.
2. Explore the potential impact of large-scale adoption of aerobic rice in regional hydrology and water availability. How much water is saved on regional basis (up to now, we focused on field scale only)? We need actual measurements of evapotranspiration (ET) rates of aerobic rice (up to know, we mostly estimated ET by simulation modeling and by water balance approaches).

Tropics

1. Varieties need to be developed with higher tolerance to aerobic soil, aiming at yield potentials of 5-6 t ha^{-1} with soil water tensions going up to 100 kPa (like with the Han Dao aerobic rice varieties in the YRB). Besides improving the tolerance to aerobic soil

conditions, tolerance to “soil sickness”, such as nematodes, fungi, or nutrient imbalances may be important in increasing yield potential as well.

2. The mechanisms of yield decline under continuous cropping and of immediate yield collapse need to be understood and remedial (management) practices developed. It is proposed to develop specifically sustainable crop rotation systems.

12. KEY PUBLICATIONS

Published Journal papers

1. Bouman, B.A.M., Feng Liping, Tuong, T.P., Lu Guoan, Wang Huaqi, Feng Yuehua, 2007. Exploring options to grow rice under water-short conditions in northern China using a modelling approach. II: Quantifying yield, water balance components, and water productivity. Agricultural Water Management 88, 23-33.
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3. Lixiao Nie, Shaobing Peng, Bas A. M. Bouman, Jianliang Huang, Kehui Cui, Romeo M. Visperas, and Hong-Kyu Park, 2007. Solophos fertilizer improved rice plant growth in aerobic soil. Journal of Integrated Field Science 4: 11-16.
4. Lixiao Nie, Shaobing Peng, Bas A.M. Bouman, Jianliang Huang, Kehui Cui, Romeo M. Visperas, Hong-Kyu Park, 2007. Effect of oven heating of soil on vegetative plant growth of aerobic rice. Plant and Soil 300: 185-195.

Journal papers submitted or in preparation

1. Lampayan, R.M., B.A.M. Bouman, J.E. Faronilo, J.B. Soriano, L. B. Silverio, B. V. Villanueva, J.L. de Dios, A.J. Espiritu, T.M. Norte, K. Thant, (in prep 2008), Yield of aerobic rice in rainfed lowlands of the Philippines as affected by N fertilization and row spacing.
2. Limeng Zhang, Shan Lin, Hongbin Tao, Changying Xue, Xiaoguang Yang, Dule Zhao, B.A.M. Bouman, Klaus Dittert (in prep 2008), Response of yield determinants and dry matter translocation of aerobic rice to N application on two soil types
3. Lixiao Nie, Shaobing Peng, Bas A.M. Bouman, Jianliang Huang, Kehui Cui, Romeo M. Visperas, and Jing Xiang, (in preparation 1), Alleviating soil sickness caused by aerobic monocropping: Responses of aerobic rice to nutrient supply, to be submitted to Field Crops Research.
4. Lixiao Nie, Shaobing Peng, Bas A.M. Bouman, Jianliang Huang , Kehui Cui, Romeo M. Visperas, Jing Xiang, (in preparation 2), Alleviation of Soil Sickness Caused by aerobic monocropping: Responses of rice plant to various nitrogen sources, to be submitted to Plant and Soil.
5. Xiao Qin Dai, Hong Yan Zhang, J. H. J. Spiertz, Jun Yu, Guang Hui Xie, B. A. M Bouman, (in prep 2008), Productivity and Resource Use of Aerobic Rice – Winter Wheat Cropping Systems in the Huai River Basin.

6. Xue Changying, Yang Xiaoguang, Bouman B.A.M., Deng Wei, Zhang Qiuping,Yan Weixiong, Zhang Tianyi, Rouzi Aji, Wang Huaqi,Wang Pu, (submitted), Effects of irrigation and nitrogen on the performance of aerobic rice in northern China. Journal of Integrative Plant Biology.
7. Xue Changying, Yang Xiaoguang, B.A.M. Bouman, Deng Wei, Zhang Qiuping, Yan Weixiong, Zhang Tianyi, Rouzi Aji, Wang Huaqi, (submitted), Optimizing yield, water requirements, and water productivity of aerobic rice for the North China Plain, Irrigation Science.

Other scientific publications

National Journal publications, proceedings, book chapters. Some papers report only on CPWF project results, whereas in others, CPWF project results are part of the paper. We included international journal papers which include part of our CPWF project results as well.

1. Guanghui Xie, Yu Jun, Yan Jing, Wang Huaqi, Zhu Xiurong, 2007. Direct seeding of aerobic rice in China. In: Rice is life: scientific perspectives for the 21st century. IRRI, Los Banos, pp 186-188.
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5. Lampayan, R.M., B.A.M. Bouman, 2005. Management strategies for saving water and increase its productivity in lowland rice-based ecosystems. In: proceedings of the First Asia-Europe Workshop on Sustainable Resource Management and Policy Options for Rice Ecosystems (SUMAPOL), 11-14 May 2005, Hangzhou, Zhejiang Province, P.R. China. On CDROM, Altera, Wageningen, Netherlands.
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11. Xue Changying ,Yang Xiaoguang, Deng Wei, Zhang Tianyi, Yan Weixiong, Zhang Qiuping, Rouzi Aiji, Zhao Junfang, Yang Jie, Bouman. B.A.M, 2007. Yield Potential and Water Requirement of Aerobic Rice in Beijing Analyzed by ORYZA2000 Model, Acta Agronomica Sinica, Vol 33(4): 625-631.

12. Xue Changying ,Yang Xiaoguang, Deng Wei, Bouman. B.A.M, Zhang Qiuping, Yan Weixiong, Zhang Tianyi, Rouzi Aiji, Wang Huaqi, 2007. Study on Yield Potential and Water Requirement of Aerobic Rice in Beijing Area Based on ORYZA2000 Model. In: Hu Yuegao,Huang Guohe, Li Zhaohu (Eds), Principles and Practices of Desertification Control, Proceedings of the international specialty conference on science and technology for desertification control. China Meteorological Press, Beijing, China. Pp: 435-451.

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1. A "Grain of Truth" on aerobic rice in the journal Rice Today (Published by IRRI), June 2007.
2. An article on aerobic rice in Ripple, June 2007 (IRRC newsletter)
3. A feature article in Rice Today (special issue October 2007): "Aerobic rice farming with less water —fighting the irrigation crisis", by Adam Barclay.

Training materials

Bouman, B.A.M., R.M., Lampayan, T.P. Tuong, 2007. Water management in Rice: coping with water scarcity. Los Baños, (Philippines): International Rice Research Institute, 54 pp. The chapter on aerobic rice was contributed by the CPWF project

Powerpoint presentation as part of training series on water management: aerobic rice module. A number of Chinese-language presentations and information leaflets. Various flipcharts, posters, leaflets produced by local project partners as used in farmer field schools and other training events.

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APPENDICES

Appendix A: Abstracts of all key publications

Bouman, B.A.M., Feng Liping, Tuong, T.P., Lu Guoan, Wang Huaqi, Feng Yuehua, 2007. Exploring options to grow rice under water-short conditions in northern China using a modelling approach. II: Quantifying yield, water balance components, and water productivity. Agricultural Water Management 88, 23-33.

Abstract

Because of increasing competition for water, water-saving technologies such as alternate wetting and drying and aerobic rice are being developed to reduce water use while maintaining a high yield of rice. The components of the water balance of these systems need to be disentangled to extrapolate water savings at the field scale to the irrigation system scale. In this study, simulation modelling was used to quantify yield, water productivity, and water balance components of alternate wetting and drying and aerobic rice in the conjunctive surface-groundwater Liuyuankou Irrigation System, Henan. The study on aerobic rice was supported by on-farm testing. In the lowland rice area, where groundwater tables are within the root zone of the crop, irrigation water savings of 200-900 mm can be realized by adopting alternate wetting and drying or rainfed cultivation, while maintaining yields at 6400-9200 kg ha^{-1}. Most of the water savings are caused by reduced percolation rates, which will reduce groundwater recharge and may lead to decreased opportunities for groundwater irrigation. Evaporation losses can be reduced by a maximum of 60-100 mm by adopting rainfed cultivation. In the transition zone between lowland rice and upland crops, groundwater tables vary from 10 cm to more than 200 cm depth, and aerobic rice yields of 3800-5600 kg ha^{-1} are feasible with as little as 2-3 supplementary irrigations (totaling 150-225 mm of water). Depending on groundwater depth and amount of rainfall, either groundwater recharge or net extraction of water from the soil or the groundwater takes place.

Feng Liping, Bouman, B.A.M., Tuong, T.P., Cabangon, R.J., Li Yalong , Lu Guoan, Feng Yuehua, 2007. Exploring options to grow rice under water-short conditions in northern China using a modelling approach. I: Field experiments and model evaluation. Agricultural Water Management 88, 1-13.

Abstract

China's grain basket in the North China Plain is threatened by increasing water scarcity and there is an urgent need to develop water-saving irrigation strategies. Water savings in rice can be realized by alternate wetting and drying (AWD) under lowland conditions, or by aerobic rice in which the crop is grown under nonflooded conditions with supplemental irrigation. Field

experimentation and simulation modelling are a powerful combination to understand complex crop-water interactions and to extrapolate site-specific empirical results to other environments and conditions. In this paper, we present results from four years of field experiments on AWD and aerobic rice in 2001-2004 near Kaifeng, Henan Province, China. The experimental data were used to parameterize and evaluate the rice growth model ORYZA2000. A subsequent paper reports on the extrapolation of the experimental results using ORYZA2000 and on farmer-participatory testing of aerobic rice. In the lowland area of the study site, rice yields under flooded conditions were around 8000 kg ha^{-1} with 900 mm total (rain, irrigation) water input. Irrigation water savings were 40-70% without any yield loss by applying AWD. In the upland area of the study site, aerobic rice yielded 2400-3600 kg ha^{-1}, using 750-1100 mm total water input. ORYZA2000 satisfactorily reproduced the dynamics in measured crop variables (biomass, leaf area, N uptake) and soil water variables (ponded water depth, soil water tension). The root mean square error of predicted yield was 11% for lowland rice and 19% for aerobic rice, which was only one and a half times the error in the measured values. We concluded that ORYZA2000 is sufficiently accurate to extrapolate our results on AWD and aerobic rice to different management and environmental conditions in our study area.

R.M. Lampayan, B.A.M. Bouman, J.E. Faronilo, J.B. Soriano, L. B. Silverio, B. V. Villanueva, J.L. de Dios, A.J. Espiritu, T.M. Norte, K. Thant, (in prep), Yield of aerobic rice in rainfed lowlands of the Philippines as affected by N fertilization and row spacing.

Abstract.

This study evaluated the effects of different N amount and timing of N applications and row spacings on yields of aerobic rice under rainfed conditions in Central Luzon, Philippines. Two field experiments were conducted: (a) nitrogen amount by row spacing (NA x RS) experiment in San Ildefonso, Bulacan and in Dapdap, Tarlac during 2004 and 2005 wet season, and (b) N-split application by row spacing (NS x RS) in PhilRice during 2004 wet season and 2005 dry season. All experiments were laid out in a split-plot design with four replications using Apo cultivar, and nitrogen as mainplot and row spacing as subplot. In the NA x RS experiment, five N levels were used: 0, 60, 90, 120 and 150 kg ha^{-1}. For NS x RS, a total fixed rate of 100 kg ha^{-1} was applied, but under five different timing of application in percent: 0-30-30-30-10 (NS_1), 0-20-50-30-0 (NS_2), 0-20-30-50-0 (NS_3), 23-23-29-25-0 (NS_4), and 18-0-29-43-10 (NS_5) at the following schedules: 0 DAE (basal), 10-14 DAE, 30-35 DAE, 45-50 DAE and 60 DAE. Three row spacings were used in both experiments: 25 cm (RS_{25}), 30 cm (RS_{30}), and 35 cm (RS_{35}). Results showed that under rainfed condition, about 3.1 to 4.9 t ha^{-1} of grain yields of aerobic rice can be obtained with addition of 60-150 kg N ha^{-1}. Grain yields increased with higher application of nitrogen fertilizers, but beyond N level of 90 kg ha^{-1}, the risk of lodging may pose a problem especially in the wet season. N-split treatments did not generally affect grain yields, and the common practice of three to four split applications of N-fertilizer at major crop growth stages of flooded lowland rice showed is also applicable for aerobic under rainfed condition. Grain yields were not affected by differences of row spacing. Although the number of panicles per square meter in the narrow row

spacing (25 cm) was significantly higher than in the wider spacing (35 cm), this difference was compensated for by the significantly higher number of spikelet per panicle in the wider spacing. The percent filled spikelet was also slightly higher in the wider spacing than in the narrow spacing. We did find significant effect of row spacings on percent lodging. While the optimum combination of N level and row spacing on grain yield and bending resistance of aerobic rice was not identified, results suggested that farmers may grow aerobic rice using row spacing within 25-35 cm as long as this row spacing may not interfere with other cultural management practices.

Limeng Zhang, Shan Lin, Hongbin Tao, Changying Xue, Xiaoguang Yang, Dule Zhao, B.A.M. Bouman, Klaus Dittert (in prep 2008), Response of yield determinants and dry matter translocation of aerobic rice to N application on two soil types

Abstract

At the background of increasing water scarcity, a new type of water-saving rice, aerobic rice has been developed recently. Little is known about the crop performance and nutrient uptake in response to nitrogen management and soil types such as lowland and upland soils. Therefore, in 2005-2006, field experiments were conducted with aerobic rice cv. Han Dao 297 (Hereafter, HD297) under different N fertilizer levels and irrigation regimes on a traditional lowland soil (Shangzhuang site) and an upland soil (CAU site) near Beijing, North China. The nitrogen rates were 0 kg N ha^{-1} (N0), 75 kg N ha^{-1} (N1) and 150 kg N ha^{-1} (N2), split applied at a ratio of 3:4:3 given at sowing, tillering and booting stage. The irrigation management was based on the soil water potential at 15 cm depth maintaining soil moisture at around -20 kPa through the entire growing season (W1), at -40 kPa from emergence to PI, at -20 kPa from PI to flowering and at -40 kPa after flowering (W2), and at -60 kPa over the entire season (W3). Aerobic rice HD297 yielded 3.1 to 5.3 ton ha^{-1} as influenced by N fertilizer rates and site conditions. At Shangzhuang site in 2005, HD297 combined a high aboveground biomass (15.6 t dry matter ha^{-1}) with a low harvest index (averaged 0.30) at the seeding rate 135 kg/ha. Little effect of nitrogen on grain yield was observed. In 2006, pre-anthesis dry matter production, tiller numbers and LAI clearly increased with increasing N fertilizer rates at both sites. However, during grain filling, differences in dry matter were only small, and in some cases, differences in pre-anthesis dry matter were compensated. Dry matter translocation from vegetative organs into grains increased with N fertilizer rates, but the mean translocated dry matter was relatively low, with only 1.08 t DM ha^{-1}. Dry matter translocation efficiency ranged from 3.7-34.9 %. And the contribution of pre-anthesis assimilates to grain was 10.9-65.7 % differed with N supply. Low dry matter translocations associated with a sharp decrease in LAI after flowering. And poorer percent filled grains with higher N supply were exhibited. On average across treatments, 13 % greater grain yield was produced at Shangzhuang site than at CAU site. Higher dry matter production and greater spikeltets per m^2 at Shangzhuang site contributed to the higher grain yield compared to CAU site.

Lixiao Nie, Shaobing Peng, Bas A. M. Bouman, Jianliang Huang, Kehui Cui, Romeo M. Visperas, and Hong-Kyu Park, 2007. Solophos fertilizer improved rice plant growth in aerobic soil. Journal of Integrated Field Science 4: 11-16.

Abstract

Yield decline of continuous monocropping of aerobic rice is the major constraint to the wide adoption of aerobic rice technology. This study was conducted to determine if solophos fertilizer could be used to reverse the yield decline of this cropping system using pot and micro-plot experiments. The soil for the pot experiment was collected from a field where aerobic rice has been grown continuously for 11 seasons at the IRRI farm. Four rates (4, 6, 8, and 10 g pot^{-1}) of solophos application were used in the pot experiment. Micro-plots (1 × 1 m) were installed in the field experiment where the 12th-season aerobic rice was grown. Treatments in the micro-plots were with and without additional solophos application. Solophos rate was 4,407.5 kg ha^{-1} which was equivalent to 10 g solophos pot^{-1} used in the pot experiment. An improved upland variety, Apo, was used for both pot and micro-plot experiments. Application of solophos significantly increased plant height, stem number, leaf area, chlorophyll meter reading, root dry weight, and total biomass in the pot experiment. The growth enhancement by solophos application was also observed in the micro-plot experiment under the field conditions. Photosynthetic rate and spikelet number per m^2 were increased by solophos application in the micro-plot experiment. Although the mechanism of growth promotion by solophos application is not clear, this study suggested that solophos application can be used as one of crop management options that could minimize the yield decline of continuous monocropping of aerobic rice.

Lixiao Nie, Shaobing Peng, Bas A.M. Bouman, Jianliang Huang, Kehui Cui, Romeo M. Visperas, Hong-Kyu Park, 2007. Effect of oven heating of soil on vegetative plant growth of aerobic rice. Plant and Soil 300: 185-195.

Abstract

"Aerobic rice" system is the cultivation of nutrient-responsive cultivars in nonflooded and nonsaturated soil under supplemental irrigation. It is intended for lowland areas with water shortage and for favorable upland areas with access to supplementary irrigation. Yield decline caused by soil sickness has been reported with continuous monocropping of aerobic rice grown under nonflooded conditions. The objective of this study was to determine the growth response of rice plant to oven heating of soil with a monocropping history of aerobic rice. A series of pot experiments was conducted with soils from fields where rice has been grown continuously under aerobic or anaerobic (flooded) conditions. Soil was oven heated at different temperatures and for various durations. Plants of Apo, an upland variety that does relatively well under the aerobic conditions of lowland, were grown aerobically without fertilizer inputs in all six experiments. Plants were sampled during vegetative stage to determine stem number, plant height, leaf area, and

total biomass. Heating of soil increased plant growth greatly in soils with an aerobic history but a relatively small increase was observed in soils with a flooded history as these plants nearly reached optimum growth. A growth increase with continuous aerobic soil was already observed with heating at 90 °C for 12 hours and at 120 °C for as short as 3 hours. Maximum plant growth response was observed with heating at 120 °C for 12 hours. Leaf area was most sensitive to soil heating, followed by total biomass and stem number. We conclude that soil heating provides a simple and quick test to determine whether a soil has any sign of sickness that is caused by continuous cropping of aerobic rice.

Lixiao Nie, Shaobing Peng, Bas A.M. Bouman, Jianliang Huang, Kehui Cui, Romeo M. Visperas, and Jing Xiang, (in preparation 1), Alleviating soil sickness caused by aerobic monocropping: Responses of aerobic rice to nutrient supply, to be submitted to Field Crops Research.

Abstract

Yield decline is a major constraint in the adoption of continuous cropping of aerobic rice. The causes of the yield decline in the continuous aerobic rice system are still unknown. The objective of this study was to determine if nutrient application can mitigate the yield decline caused by continuous cropping of aerobic rice. Micro-plot experiment was conducted in 2005 dry season (DS) in a field where aerobic rice has been grown continuously for eight seasons from 2001 DS at the International Rice Research Institute (IRRI) farm. Pot experiments were done with the soil from the same field where the micro-plot experiment was conducted and aerobic rice has been grown continuously for 10 seasons. Apo, an upland rice variety, was grown under aerobic conditions with different nutrient inputs in field and pot experiments. The micro-plot experiment showed that micronutrients had no effect on plant growth under continuous aerobic rice cultivation but the combination of N, P, and K mitigated the yield decline of continuous aerobic rice. A series of pot experiments studying the individual effects of nutrients indicated that N application improved plant growth under continuous aerobic rice cropping, while P, K, and micronutrients had no effect. Increasing the rate of N application from 0.23 to 0.90 g per pot in the continuous aerobic rice soil increased the vegetative growth parameters, chlorophyll meter readings, and aboveground N uptake consistently. Our results suggested that N deficiency due to poor soil N availability or reduced plant N uptake might cause the yield decline of continuous cropping of aerobic rice.

Lixiao Nie, Shaobing Peng, Bas A.M. Bouman, Jianliang Huang , Kehui Cui, Romeo M. Visperas, Jing Xiang, (in preparation 2), Alleviation of Soil Sickness Caused by aerobic monocropping: Responses of rice plant to various nitrogen sources, to be submitted to Plant and Soil.

Abstract

Yield decline of continuous cropping of aerobic rice is the major constraint to the wide adoption of aerobic rice technology. This study was conducted to examine the differences in plant growth responses to different N sources applied in the continuous aerobic rice soil. Soils for pot experiments were collected from two adjacent fields at the International Rice Research Institute (IRRI) farm: an aerobic field where aerobic rice has been grown continuously for 11 seasons from 2001 dry season (DS) and a flooded field where flooded rice has been grown continuously. The results showed that application of additional N significantly increased the plant growth and grain yield of aerobic rice in continuous aerobic rice system. Among the nitrogen fertilizers tested, ammonium sulfate was the most effective in improving plant growth under the continuous aerobic soil. The plant growth, grain yield, total biomass, N content in grains and aboveground N uptake of plants fertilized with ammonium sulfate were relatively higher than those fertilized with urea, when the N rate was above 0.6 g N pot^{-1}. Furthermore, the differences in these parameters between ammonium sulfate and urea applications increased as the N rate increased. Additional pot experiment using the continuous aerobic soil was conducted to examine the effect of ammonium sulfate in Apo, IR80508-B-57-3-B, and IR78877-208-B-1-2. Ammonium sulfate consistently and significantly improved plant growth in the three genotypes. Our experiments suggested that ammonium sulfate may be used to mitigate the yield decline caused by continuous cropping of aerobic rice and that it is possible to reverse the yield decline by using of N efficient genotypes in combination of improved N management strategies.

Xiao Qin Dai, Hong Yan Zhang, J. H. J. Spiertz, Jun Yu, Guang Hui Xie, B. A. M Bouman, (in prep 2008), Productivity and Resource Use of Aerobic Rice – Winter Wheat Cropping Systems in the Huai River Basin.

Abstract

Water shortage is threatening conventional irrigated rice production, prompting the introduction of water-saving rice production systems in China. Considerably savings on irrigation water are possible by growing rice in a non-flooded aerobic soil. In aerobic rice systems soil aeration status and nutrient availability differ from flooded lowland systems. This may affect nutrient availability within one crop cycle, but also over a cropping sequence. However, the response of aerobic rice to nutrients and its use efficiency in a cropping sequence has hardly been documented. To study these responses, a field experiment was conducted with aerobic rice - winter wheat (AR-WW) and winter wheat - aerobic rice (WW-AR) cropping sequences in the Huai River Basin, China. Fertilizer treatments comprised of a standard NPK dose, a PK dose (N omission),a NK dose (P omission), a NP dose (K omission) and a control with no fertilizer input. Omission of N reduced yield by 0.5 ~ 0.8 Mg ha^{-1} for aerobic rice and 2.3 ~ 4.3 Mg ha^{-1} for winter wheat. The yield loss was less when only P or K was omitted, indicating that N was the most limiting nutrient for both crops. For the whole cropping system (aerobic rice + winter wheat), grain yield decreased by 44, 11 and 7% for N, P and K omission in the AR-WW sequence and by 30, 6 and 0% for N, P and K omission in the WW-AR sequence, indicating that the cumulative effects of N, P or K omission on yield were greater in the AR-WW than the WW-AR sequence. Generally, omissions of N, P and K decreased

the nutrient concentrations of various plant parts and the total nutrient uptake of aerobic rice and winter wheat. Nitrogen, P and K concentration of aerobic rice in WW-AR and of winter wheat in AR-WW sequence were respectively lower than those in another corresponding sequence, indicating that nutrient depletion by the preceding crops further decreased the nutrient concentration of the following crops. Nutrient uptake by aerobic rice and winter wheat was significantly influenced by the fertilizer treatments and differences in uptake were associated with plant biomass. Aerobic rice and winter wheat were more sensitive to N than to P or K omission, indicating that N was the most important limiting nutrient. Furthermore, aerobic rice responded less to nutrient omissions than winter wheat, because the latter had a higher nutrient demand. The highest nutrient use efficiencies were associated with a low nutrient availability and low yields. The challenge should be to improve crop productivity and resource use efficiency simultaneously not only for one individual crop, but for the whole cropping system. To combine high nutrient use efficiencies and productivity, an appropriate well-balanced fertilizer management is required.

Xue Changying, Yang Xiaoguang, Bouman B.A.M., Deng Wei, Zhang Qiuping, Yan Weixiong, Zhang Tianyi, Rouzi Aji, Wang Huaqi,Wang Pu, (submitted), Effects of irrigation and nitrogen on the performance of aerobic rice in northern China. Journal of Integrative Plant Biology.

Abstract

Aerobic rice is a new production system in which specially-developed varieties are grown under nonflooded, nonpuddled, and nonsaturated soil conditions. Insight is needed into water and fertilizer N response and water by N interaction to develop appropriate management recommendations. In 2003-2004, irrigation x N experiments were done near Beijing using variety HD297. Water treatments included four irrigation levels, and N treatments included different fertilizer N application rates and different number of N splits. The highest yields were 4.5 t ha^{-1} with 688 mm of total (rain plus irrigation) water input in 2003 and 6.0 t ha^{-1} with 705 mm of water input in 2004. Because of quite even distribution of rainfall in both years, the four irrigation treatments did not result in large differences of soil water conditions. There were few significant effects of irrigation on biomass accumulation, but yield increased with total amount of water applied. High yields coincided with high harvest index and high percentage of grain filling. The application of fertilizer N either reduced biomass and yield or kept it at the same level as 0 N and consistently reduced percentage grain filling and 1000-grain weight. There were no or inconsistent interactions between water and N. With the highest water application, five splits of N gave higher yield than three splits, whereas three splits gave higher yield than five splits with lower water applications. High yields with 0 N were probably caused by frequent overfertilization in the past, leading to high levels of indigenous soil N supply. A longer-term (over three years) experiment may be needed to quantify the N response of aerobic rice and how much N fertilizer can be saved in N-saturated soils.

Xue Changying, Yang Xiaoguang, B.A.M. Bouman, Deng Wei, Zhang Qiuping, Yan Weixiong, Zhang Tianyi, Rouzi Aji, Wang Huaqi, (submitted), Optimizing yield, water requirements, and water productivity of aerobic rice for the North China Plain, Irrigation Science.

Abstract

Water resources for agricultural are rapidly declining in the North China Plain because of increasing industrial and domestic use and because of decreasing rainfall resulting from climate change. Water-efficient agricultural technologies need to be developed. Aerobic rice is a new crop production system in which rice is grown in nonflooded and nonsaturated aerobic soil, just like wheat and maize. Although an estimated 80,000 ha are cultivated to aerobic rice in the plain, there is little knowledge on obtainable yields and water requirements to assist farmers in improving their management. We present results from field experiments with aerobic rice variety HD297 near Beijing, 2002-2004. The crop growth simulation model ORYZA2000 was used to extrapolate the experimental results to different weather conditions, irrigation management, and soil types. We quantified yields, water inputs, water use, and water productivities. On typical freely-draining soils of the North China Plain, aerobic rice yields can reach 6-6.8 t ha^{-1}, with, on average some 477 mm rainfall and 112-320 mm of irrigation water. The irrigation water can be supplied in 2-4 applications and should aim at keeping the soil water tension in the root zone below 100-200 kPa. Under those conditions, the amount of water use by evapotranspiration is 458-483 mm. The water productivity with respect to total water input (irrigation plus rainfall) is 0.89-1.05 g grain kg^{-1} water, and with respect to evapotranspiration, 1.28-1.42 g grain kg^{-1} water. Drought around flowering should be avoided to minimize the risk of spikelet sterility and low grain yields. The simulations suggest that, theoretically, yields can go up to 7.5 t ha^{-1} and beyond. Further research is needed to reveal whether the panicle (sink) size is large enough to support such yields and/or improved management is needed.

Appendix B: Ten Frequently Asked Questions and answers

What is aerobic rice?

Aerobic rice is a production system in which specially developed, input-response rice varieties with "aerobic adaptation" are grown in well-drained, nonpuddled, and nonsaturated soils without ponded water, with a management system aiming at yield levels of 4-6 t ha^{-1} (and possibly beyond). A nonsaturated soil is also called an "aerobic soil".

What are aerobic rice varieties?

Varieties adapted to aerobic management systems require the ability to maintain rapid growth in soils with moisture content at or below field capacity. They share this ability with traditional upland rice varieties, which usually have deep root systems and tolerate water stress at both the vegetative and reproductive stages. However, varieties for aerobic production systems also need to be able to produce yields of 4-6 t ha^{-1} under favorable conditions. Traditional upland varieties, which are usually low-tillering, tall, and have a low harvest index, rarely achieve yields higher than 3 t ha^{-1} even under the most favorable conditions. Achieving high yields under aerobic soil conditions requires new varieties of "aerobic rice" that combine the drought-resistant characteristics of upland varieties with the high-yielding characteristics of lowland varieties.

Aerobic rice varieties combining high yield potential with tolerance to aerobic soil conditions have usually been derived from breeding programs in which varieties are developed and evaluated under aerobic soil conditions and with fertilizer applications sufficient for a 4-6 t ha^{-1} yield target. The first generation of varieties that performed well in a wide range of aerobic rice environments (e.g. IR55423-01 ("Apo") and UPLRI-5 from the Philippines, B6144-MR-6-0-0 from Indonesia, and CT6510-24-1-2 from Colombia) were developed in upland rice breeding programs. They were often derived from crosses between *indica* and tropical *japonica* parents, whereas traditional upland varieties are usually derived from the *aus* or tropical *japonica* germplasm groups. Some aerobic rice breeding programs, (notably that of the China Agricultural University in Beijing), also have developed successful varieties by crossing high-yielding lowland rice varieties with traditional upland types. In northern China, new elite aerobic varieties were released in the late 1990s such as Han Dao 277, Han Dao 297 and Han Dao 502, with yield potentials of up to 6.5 t ha^{-1}.

What is the difference between aerobic rice and upland rice?

Upland rice is grown in rainfed, naturally well-drained soils with bunded or unbunded fields without surface water accumulation. The general perception about the upland environment is that it is drought-prone, usually sloping land with erosion problems, and has soils with both poor physical and chemical properties. Farmers in these environments are among the poorest and usually can not afford to apply (many) external inputs such as fertilizers. Upland rice varieties are mostly grown as a low-yielding subsistence crop to give stable yields under the adverse environmental conditions of the uplands. Upland rice varieties are drought tolerant, but have a low yield potential and tend to lodge under high levels of external inputs such as fertilizer and supplemental irrigation.

The aerobic rice system is targeted at more favorable environments (see below) where farmers can afford to buy external inputs such as fertilizers and have access to supplementary irrigation if rainfall is not sufficient. Achieving high yields under relatively favorable aerobic soil conditions requires new varieties of "aerobic rice" that combine the drought-resistant characteristics of upland varieties with the high-yielding characteristics of lowland varieties. In essence, aerobic rice can be seen as "favorable" or "high yielding" upland rice. The reason for the introduction of a new term was the need to dissociate the envisioned relatively high-yielding production system from the general perception of extremely harsh and unfavorable conditions of "the uplands".

Why aerobic rice?

There are three main driving forces for aerobic rice:

1. The increasing realization that not all "uplands" are "unfavorable", in the sense that certain uplands may possess soils with good water-holding capacity and high fertility, that they are not always sloping land, that rainfall may be sufficient for a "decent' crop growth, and that sometimes investments can be made to improve the quality of the uplands. An example of the latter is the terracing of slopes in the hilly and mountainous regions in Yunnan, China, and in North Vietnam. Aerobic rice is seen as a relatively high-yielding production system that optimally exploits the resources available. Other examples of "favorable" uplands are the flat Cerrado region in Brazil, and the North China Plain where aerobic rice is introduced in typical high-yielding upland cropping systems (such as maize, cotton, soybean).
2. The increasing awareness that many areas in the so-called "rainfed lowlands" don't receive enough water to keep the rice fields predominantly flooded. Rainfed lowlands are often characterized by slightly undulating topography with differences in elevation of a few meters across a toposequence of a few hundred meters only. Because of this topography, however, fields at the top of a toposequence often have deep groundwater tables, more coarse-textured soils, and more runoff and seepage losses. The soils in these fields are often dominantly aerobic and hence an ideal target domain for the system of aerobic rice.
3. The increasing water scarcity in irrigated lowlands. The causes for water scarcity are diverse and location-specific, but include decreasing resources (*e.g.*, falling groundwater tables, silting of reservoirs), decreasing quality (*e.g.*, chemical pollution, salinization), malfunctioning of irrigation systems, and increased competition from other sectors such as urban and industrial users. In extreme cases, water scarcity can be so severe that farmers can not maintain flooded conditions in their fields for even a small part of the growing season, and rice fields are not ponded and saturated with water anymore. However, irrigation water availability is still sufficient for supplementary irrigation to keep the soil water content around field capacity. Under such conditions, lowland rice can not be grown

anymore, and aerobic rice becomes a suitable alternative along with upland crops (diversification).

Where aerobic rice?

Aerobic rice can be found, or can be a suitable technology, in the following major rice-growing environments:

1. So-called "favorable uplands" (see FAQ 4: Why aerobic rice?): areas where the land is flat (or terraced), where rainfall with or without supplemental irrigation is sufficient to frequently bring the soil water content close to field capacity, where no serious soil-chemical limitations such as aluminium toxicity or salinity occur, and where farmers have access to external inputs such as fertilizers. A typical example is in the Cerrado region of Brazil, where farmers grow aerobic rice in rotation with crops such as soybean and fodder on large commercial farms with supplemental sprinkler irrigation on an estimated 250,000 ha of flat lands, realizing yields of 3-4 t ha^{-1}. Another example is rainfed aerobic rice grown in newly-formed terraces in the hills of Yunnan, China, where yields are also typically 3-4 t ha^{-1}.

2. Fields on upper toposequence locations in undulating so-called "rainfed lowlands". Quite often, the soils of such upper fields or terraces are relatively coarse-textured and well-drained, so that ponding of water only occurs for a limited (or no) part of the growing season. No widespread examples of aerobic rice in rainfed lowlands are known, but these upper fields have been proposed as target domain for aerobic rice.

3. Water-short irrigated lowlands (see FAQ 4: Why aerobic rice?): areas where farmers do not have access to water to keep rice fields flooded for a substantial period of time anymore. Water shortage can be encountered in tail-end parts of large-scale surface irrigation systems, in areas where the groundwater has been drawn down so that pumping costs have become very high, in irrigation systems that receive less and less water because of redirected use (cities, industry) or because of reduced stream flow in rivers. A good example is the North China Plain where aerobic rice is grown on about 80,000 ha with supplemental irrigation.

Beside these typical rice-growing environments, aerobic rice can also be found in traditionally non-rice growing areas. Again in the North China Plain, farmers are experimenting with aerobic rice as a means of crop diversification in areas where traditionally maize is the dominant crop.

Aerobic rice can be found in tropical and in temperate climates. Most advances in developing aerobic rice systems, and in adoption by farmers, have been made so far in China and Brazil.

How to manage aerobic rice?

Aerobic rice is basically managed like a wheat or a maize crop. The usual establishment method is dry direct seeding. Before sowing, the land should be dry prepared by ploughing and harrowing to obtain a smooth seed bed. Seeds should be dry seeded at 1-2 cm depth in heavy (clayey) soils and 2-3 cm depth in light-textured (loamy) soils. Optimum seeding rates still need to be established but are probably in the 70-90 kg ha^{-1} range. In experiments so far, row spacings between 25 and 35 cm gave similar yields. The sowing of the seeds can be done manually (eg dibbling the seeds in slits opened by a stick or a tooth harrow) or using direct seeding machinery. An alternative establishment method is transplanting, where seedlings are transplanted into wet soil that is kept around saturation for a few days to ease transplanting shock. Subsequently the fields dry out to field capacity and beyond. This method of crop establishment can only be done in clay soils with good water-holding capacity.

An aerobic rice crop attaining 4-6 t ha^{-1} yields obtains many of its required nutrients from the soil. But this "indigenous supply" of nutrients is typically not sufficient to meet all the nutrient needs, and fertilizers will need to be applied. Site-specific knowledge about the indigenous nutrients supply is the starting point for formulating fertilizer recommendations. The site-specific nutrient management (SSNM) approach (www.irri.org/irric/ssnm) can be used to determine the need for supplemental nutrients in the form of fertilizers and the optimal management of fertilizers. A useful tool to assist in the application of nitrogen (N) fertilizer is the Leaf Color Chart (LCC; part of the SSNM approach). In the absence of trained extension personnel in SSNM and LCC, an amount of 70-90 kg N ha^{-1} could be a useful starting point (to be subsequently optimized). Instead of basal application of the first N split, the first application can best be applied 10-12 days after emergence to minimize N losses by leaching (the emerging seedling can't take up N so fast, so it will easily leach out). Moreover, basal application of N also promotes early weed growth. Second and third split applications of N may be given around active tillering and panicle initiation, respectively. Dry, aerobic, soil can reduce the indigenous supply of phosphorus (P), hence the application of fertilizer P can be more critical for aerobic rice than for conventional flooded lowland rice. On acid soils, aerobic rice will likely be less prone to zinc deficiency than flooded lowland rice; but on high pH soils with calcium carbonate, the reverse may be true.

If the crop is grown in a dry season, a light irrigation application (say 30 mm) should be given after sowing to promote emergence. Subsequent irrigation applications depend on the rainfall pattern, the depth of groundwater, and on the availability and/or cost of irrigation water. Irrigation can be applied by any means as used for upland crops: flash flood, furrow, or sprinkler.

Rice that is not permanently flooded tends to have more weed growth and a broader weed spectrum than rice that is permanently flooded. To control weeds, the use of pre- or post-emergence herbicides is recommended when the weed pressure is high, plus additional manual or mechanical (inter-row cultivation) weeding in the early phases of crop growth.

Is aerobic rice rainfed or irrigated?

Like wheat or maize, aerobic rice can be rainfed, supplementary irrigated, or fully irrigated. With groundwater tables below the root zone, a suitable total amount of water supply by rainfall and/or irrigation is probably 600-800 mm over the growing season. With deep groundwater tables and less than 400 mm, the typical traditional upland rice system with sturdy and drought-resistant upland varieties is more suitable. When subsurface hydrology, soil type, and rainfall (and/or irrigation) combine to create predominantly flooded or saturated soil conditions throughout the growing season, the typical lowland rice production system is more suitable. With clayey soils and groundwater tables below the root zone, one would need typically 1000 mm or more to maintain predominantly saturated soil conditions. However, with groundwater tables within the 20-cm root zone (as occurs in many typical irrigated lowland rice environments), as little as 400 mm can already maintain predominantly saturated soil conditions or flooding. The exact "transition zones" between upland rice and aerobic rice, and between aerobic rice and lowland rice production systems is therefore quite site-specific.

The optimum soil water condition for aerobic rice is around field capacity. If rainfall is insufficient to frequently restore water contents in the soil to field capacity, irrigation can be applied if water resources are available. Irrigation can be applied through flash-flooding, furrow irrigation (or raised beds), or sprinklers. Unlike flooded rice (lowland rice), irrigation - when applied – is not used to flood the soil but to just bring the soil water content in the root zone up to field capacity. The amount of irrigation water should match evaporation from the soil and transpiration by the crop (plus any application inefficiency losses). In lowland rice, the amount of irrigation water should match the same water flows, plus the losses by seepage and percolation.

Is aerobic rice a "mature" technology?

Aerobic rice can be considered quite a mature technology in temperate and subtropical environments such as northern China and Brazil, where the areas of aerobic rice are estimated at 80,000 ha and 250,000 ha, respectively. In both countries, breeding programs since the 1980s have resulted in the release of several high-yielding "aerobic rice" varieties. On-farm yield levels seem to lie around 3-4 t ha^{-1}, but yields of up to 6 t ha^{-1} have been recorded as well. Current research focuses on the development of improved management systems and on breeding further improved varieties.

Tropical aerobic rice systems are still very much in the research and development phase. More research is especially needed to breed high-yielding aerobic rice varieties with sufficient aerobic adaptation and to develop sustainable management systems. Without ponded water, rice production is less sustainable than under flooded (lowland) conditions, and typical problems come up that occur in upland crops (see FAQ 10: How sustainable is aerobic rice?). In general, sustainability seems to be more of a problem in tropical areas than in temperate areas such as northern China. Aerobic rice should not be grown consecutively on the same piece of land, and – depending on the cropping history and soil type – low yields can even occur on fields cropped to aerobic rice the very first time.

How about aerobic rice and conservation agriculture?

With aerobic rice, practices of conservation agriculture, such as mulching and minimum tillage as practiced in upland crops, become available to rice farmers as well. In the Indo-Gangetic Plain, farmers are experimenting with minimum tillage practices and permanent raised beds in the rice-wheat system. Pioneering research and development work is being done by the Rice Wheat Consortium (http://www.rwc.cgiar.org/index.asp).

Various methods of mulching (e.g., using dry soil, straw, and plastic sheets) are being experimented with in aerobic rice systems in China. In hilly areas in Shiyan, Hubei Province in China, farmers on an estimated 6000 ha are adopting the use of plastic sheets to cover rice fields in which the soil is kept just below saturation. The proclaimed advantages are: earlier crop establishment (rice is established in early spring when temperatures are still low, and the plastic sheet increases the soil temperature), higher yields, less weed growth, and less water use (important during dry spells). The left-over plastic after harvest may cause environmental degradation if not properly taken care of.

How sustainable is aerobic rice?

Given assured water supply, lowland rice fields are extremely sustainable and able to produce continuously high yields, even under continuous double or triple-cropping a year. Flooding of rice fields has beneficial effects on soil acidity (pH), soil organic matter buildup, phosphorus, iron, and zinc availability, and biological N fixation that supplies the crop with additional N. When fields are not continuously flooded, such as in aerobic rice, these beneficial effects gradually disappear. A change from flooded to aerobic soil conditions may decrease the soil organic matter content, decrease the soil pH, and decrease the availability of phosphorus, iron, and – on calcareous soils - zinc. Also, problems with micro-nutrient deficiencies have been reported. If field were cropped to rainfed rice with alternate periods of flooding and dry soil, or if fields were previously cropped to upland crops, then the introduction of aerobic will have fewer consequences for these sustainability parameters.

There are indications that soil-borne pests and diseases such as nematodes, root aphids, and fungi occur more in aerobic rice than in flooded rice, especially in the tropics. The current experience is that aerobic rice should not be grown continuously on the same piece of land each year (as can be successfully done with flooded rice) without yield decline. Suitable crop rotations need to be identified, but will be site-specific and responsive to markets.

Current research focuses on determining the causes of yield decline under continuous cropping (biotic, abiotic), on developing “resistant” varieties, on developing suitable management options such as crop rotation, and on developing integrated weed management practices.

Appendix C: Detailed recommendations for further research

Liz Humphreys, CPWF Theme Leader, (November 2007)

The development of systems of aerobic rice for tropical and temperate environments (STAR) is very important, with huge potential benefits to hundreds of millions of people in terms of food security, livelihoods and the environment.

There has been a lot of progress in the development of STAR – from understanding the genetics and mechanisms of drought tolerance, to improved varieties and how to manage them for optimal land and water productivity.

However there is still much to do – the work has hardly begun apart from in China and to a lesser degree in Philippines. Aerobic rice may be beneficial in many other regions, especially in South Asia, in both water scarce irrigated areas and favourable rainfed uplands.

The challenge will be to identify the most important research and development priorities from the plethora of possible activities. Some of the areas which I think need further emphasis are:

1. **Impact of widespread adoption on regional hydrology and ecology**

There is a lot of publicity about and emphasis on irrigation water savings with aerobic rice, but almost no consideration of total water savings, which are likely to be much less than irrigation water savings. Irrigation water savings are important, meaning increased efficiency of resources such as energy for pumping groundwater. However some or much of the savings may be due to reduced deep drainage into the groundwater, or reduced runoff. Where groundwater and runoff can be used elsewhere in the system (recycling), this is not a water saving.

There need to be:

- further studies quantifying components of the water balance for aerobic rice for a few case study situations – field experimentation and application of crop models
- education of researchers and extensionists on irrigation water savings versus system water savings (reduced depletion to sinks), so that water resource managers and policy makers are aware of the absolute water requirements of aerobic rice systems
- regional scale studies of the impacts of widespread adoption of aerobic systems on the regional hydrology and ecology

2. **Start developing aerobic systems incorporating "conservation agriculture" approaches**

Temperate and sub-tropical drill seeded aerobic rice systems are likely to be well-suited to take advantage of the benefits of conservation agriculture (reduced tillage, mulching, crop rotation, brown manuring). Such an approach would help conserve soil moisture, increase soil fertility and control diseases. It may be beneficial to develop links with individuals/groups with expertise in conservation agriculture, including those from PN12 in China and Mexico (CIMMYT) and several groups with experience in rice-wheat systems in South Asia.

Such work needs to be long term, and could be incorporated in the long term trials suggested below.

3. **Long term trials with multi-disciplinary teams**

There are issues about the sustainability of aerobic rice systems. In some situations, yields decline after a couple of crops. Long term trials are needed across a range of situations (soil, climate)

There are also many potential causes of aerobic rice not reaching potential yields. A multidisciplinary approach involving teams of scientists is needed to explain crop and system performance. Such teams would include breeders, agronomists, crop physiologists, soil chemists, soil biologists, water scientists, economists etc.

AK Singh's group at IARI, India have a couple of very good examples of long term trials involving multidisciplinary teams of researchers, and perhaps some things to learn about how to do this successfully (i.e. everyone actually contributes).

4. **Approaches to achieve rapid dissemination and widescale adoption**

Need to identify and develop approaches to achieve rapid dissemination and widescale adoption – opportunity to build on approaches introduced by CPWF to help achieve this?

5. **Systematic site characterization and monitoring**

The amount of characterization and monitoring will vary depending on the purpose, but protocols tailored to some key purposes need to be developed and disseminated to explain results, synthesis of findings across locations and develop generic understanding, and extrapolate findings across locations.

In addition to determination of baseline properties and in-season monitoring, a system of archiving soil samples may be useful for some situations to enable post experiment determination of soil properties as new knowledge and ideas arise.

e.g. <u>protocols for breeders</u> undertaking variety evaluation should include monitoring of watertable depth (simple), weather (rain, evaporation), soil type (texture of soil layers to ~0.5 m)

e.g. <u>protocols for agronomists/nutritionists</u> undertaking N management trials should include selection of sites that will be responsive to N (based on site history, soil test)

e.g. <u>protocols/proforma for rigorous financial analysis</u>

Grant Singleton, IRRC coordinator (November 2007)

From an ecologist's perspective, who is a newcomer to aerobic rice, I provide the following comments:

1. I strongly agree with Liz's comment that we need a landscape level study of the benefits of aerobic rice with respect to water savings In particular; we need to take into account the water that percolates back into the irrigation system or into streams and rivers (and therefore contributing directly to their health). I see this as a challenging but exciting research question.

2. As highlighted by Achim, we need a better understanding of factors that influence farmers in adopting/adapting an aerobic rice cropping system. Socio-economic studies have been conducted in the Philippines, and, to a lesser extent, in China. Indeed, I look forward to seeing the report from Dr. Shijun Ding from Zhongnan Univ on the impact assessment of aerobic rice in North China. Once this report is available then it would be timely to review the socio-economic lessons learned from the Philippines and China.

3. We need to be able to anticipate and then develop management practices for the impact of pests, particularly weeds, but also insects and rodents at a scale larger than a single field. I discuss nematodes in point 4.

4. The research on nematodes is progressing nicely and is impressive given the person power involved, but we need to understand further the mechanism of the host-parasite interaction. There is much that can be learned from the literature on host-parasite interactions in vertebrates, particularly the need to understand the degree of aggregation of parasites in the landscape/hosts (typically a negative geometric distribution in mammals) and the importance to quantify the intensity of infection rather than just the prevalence of infection. For example, is there a threshold level of parasite load (=intensity) before the plant defenses are unable to cope or is it a linear response?

5. To develop a better understanding of crop rotations in managing possible yield declines (including the impact of nematodes and weeds) of aerobic rice.

Achim Doberman, IRRI program Leader (November 2007)

1. Key drivers for aerobic rice include the need to locally produce rice under a lack of water, rising costs of labor and other inputs, and risk of waterlogging when upland crops are grown as alternative crops on flat land with poor drainage. The principal target areas for aerobic rice seem reasonably well understood (e.g., water-deficit lowlands with 500-900 mm rain during the growing season, lowlands and uplands with flooding risk, and sloping uplands with potential for intensification on terraced land). A first regional analysis suggests relatively large areas with potential for aerobic rice in Asia, but also Africa and South America. In Asia, the farm surveys done so far mostly show average aerobic rice yields in the 3.5-4.5 t/ha range and net returns that are mostly on par or somewhat below those of irrigated rice. But there is large variability in its performance and there are also failures. Overall, I think that much greater economic potential exists if we can further raise the genetic yield potential under aerobic cultivation conditions and fine-tune soil and crop management practices. Wide-scale adoption will probably require stable yields in the 5 t/ha range. I also see many parallels to the issues we discuss and start to address in our emerging research on diversification of irrigated rice systems towards rice-maize, for example.

2. Some confusion about terminology and cultural practices persists, particularly in China. Aerobic rice can mean quite different things in terms of cultivars used, hydrological conditions (groundwater table), number and timing of irrigations, and other crop management practices. Hence a systematic collection of information on existing practices may form the basis for a better description and classification (typology) of key aerobic rice *systems* (combinations of soil hydrology, crop rotation, cultivar types and cropping practices). This could also contribute to a more general decision tree for choosing the best cultivar and management options for maximizing productivity and water productivity in different environments, along the whole gradient of options for reducing water use in rice. Knowing soils and groundwater tables seems to be of particular importance for making the right choice. A better typology would also provide better guidance for breeding targets, target domain characterization and deployment of germplasm to different areas.

3. I suggest to conduct a more detailed biophysical and socioeconomic analysis of selected larger target domains, including a strategic assessment of what other alternatives farmers could pursue. For example, if the alternative is diversification to other crops, what <u>potential</u> (not the current average production) would those have compared to aerobic rice if both are managed right?

    a. The current household level assessments (e.g., in China) compare aerobic rice with crops such as maize or soybean, but at yield levels that do not represent achievable levels for aerobic rice and those other crops. Maize improvement is progressing fast in China and there are also management practices that could be implemented to reduce the risk of yield losses of maize or other upland crops due to waterlogging.

    b. Some of the household level studies seemed to contain somewhat confusing numbers. Since the gross margin analysis on one side depends very heavily on yield, measuring that rather than relying on what farmers report might be a major improvement by itself.

    c. The decision to grow aerobic rice or other crops is one that needs to be analyzed more systematically, also experimentally. Such an analysis could have strong linkages with IPSA activities on assessing the potential for rice-maize systems, including jointly conducted experiments that represent current and (future) optimized management practices. For example, an irrigated rice farmer in the Philippines can have a number of options for both dry and west season crops. Should he/she go for aerobic rice in the DS or WS? Where would maize fit in best? What is less risky and more sustainable? We need to develop a good framework for answering these questions, including a more standardized approach for the socioeconomic and impact assessment.

4. With the exception of cooler, long growth duration environments, current yield ceilings of aerobic rice grown in areas with low water table appear to be around 6 t/ha. Insufficient sink size and harvest indices of about 0.4 indicate potential for further breeding efforts. To make progress, breeding may have to become more focused on specific traits related to sink size, sink-source relations, and root systems.

a. I suggest that we review the management practices in the AYTs of IRRI's aerobic rice breeding program to verify that we are not selecting under unrepresentative stress conditions. Yields presented for AYTs at IRRI seemed quite low, particularly for the first generation of materials and trials conducted before 2007, when yields were mostly in the 3-4 t/ha range under so-called "non-stressed aerobic rice" (irrigated when soil moisture in 15 cm depth is less than 20 kPa). To me, such yields indicate presence of stresses other than water and we should assure ourselves that those are not related to location-specific management or other factors. Breeders need to get support from the soil scientists and agronomists for this. I think our target should be to consistently achieve DS yields in the 5.5 to 6 t/ha range for good entries in the AYTs.

b. Can simple diagnostic methods for root traits be designed for variety screening? Although one could argue that there is a relationship between (selecting for) aboveground growth and root growth, that relationships will also be location-specific and would not allow us to specifically screen for root health related traits or tolerance to nematodes. Hence, there could be value in designing doable screening methods for root traits and those could be included in the final stages of the breeding cycle, to at least screen the (few) most promising entries in more detail. The same could be done for physiological selection criteria related to yield potential, but the breeders would need more support for this.

c. I remain uncertain about the potential of breeding for adaptation to the "soil sickness syndrom" because for that to be successful we need to gain more insights on what that soil sickness actually is. To do this right would also require a much better soil and plant characterization at *plot* level (because of the patchy nature of "soil sickness"), including assessment of nematodes (roots)..

5. Agronomists have difficulties to achieve the apparent yield potential of aerobic rice cultivars and many questions remain unanswered about the causes of yield failures or yield declines. A major problem in trying to unravel causes of yield failure or yield decline is that such causes tend to be quite location-specific by nature. Unfortunately, current research on yield decline is restricted to the IRRI site because no other long-term studies exist outside IRRI.

    a. How much research should be invested in understanding the yield decline in aerobic rice? Arguments in favor are that a scientific understanding is necessary to provide accurate information on target domains and management practices for aerobic rice. Arguments against it include (i) the likelihood of site-specific causes of yield decline(s) and potential lack of a generic, *intrinsic factor* causing it, and (ii) indications that yield declines can be avoided by crop rotation or possibly also improved management of nitrogen (and other nutrients). I suggest addressing this issue as part of a broader effort that includes a set of carefully designed and managed medium- to long-term experiments in which integrated management options for aerobic rice are evaluated in comparison with other principle crop intensification or diversification options (see 3.). Now is the time to establish those, particularly in key target areas that are or may soon be undergoing a transition to aerobic rice or other crops.

b. Understanding causes of sudden yield failures (e.g., those observed in the Philippines) may be the more important challenge. Why, for example, this does not seem to occur in China is an important question to study. Besides events of extreme nematode infestations, nutritional problems also seem to sit at the heart of these failures, but including interactions with biotic stresses that may make aerobic rice plants more susceptible to such stresses. In addition to the good diagnostic work that has been done so far, better monitoring of yields, roots and soils and other key characteristics in major aerobic rice areas may be required, as part of a more strategic assessment (see 3.).

c. It appears that there is much scope for fine-tuning the management of aerobic rice to get closer to the yield potential claimed by breeders. There may be four areas of particular importance for closing yield gaps: (i) sustainable cropping systems (rotations, management and germplasm that avoid biotic stresses and undesirable changes in soil nutrient supply, including soil pH increases), (ii) fine-tuning of irrigation timing to avoid water stress in the most critical periods (flowering), (iii) fine-tuning of N management (timing, N sources, and possibly even N placement), (iv) improved micronutrient management guidelines (and diagnostics) for aerobic rice. Much of what we know for flooded rice is probably not directly applicable to aerobic rice. It may be time to explore SSNM concepts for aerobic rice, including a stronger emphasis on micronutrients.

6. Continue doing more below-ground work. Major differences in physico-chemical and biological soil processes exist between aerobic and flooded rice systems that affect the dynamics of many nutrients, but not many comprehensive studies have been conducted. Gradual changes in soil chemical properties and behavior may have contributed much to the yield decline under aerobic rice at IRRI, which appears to be somewhat reversible by applying more N, particularly acidifying N sources.

   a. For some nutrients such as phosphorus, the mechanisms affecting changes in availability under flooded vs. aerobic conditions are well understood and I see less need to work on that. Nitrogen and micronutrients are probably the major issues to focus on, particularly in relation to pH profiles across the root surface to bulk soil profile, and how all that is affected by different management practices and also cultivar differences.

   b. I think it is of particular importance to understand the major differences in rhizosphere chemistry and microbiology between aerobic and flooded rice and also genotypic variation in this. Germplasm adapted to aerobic soil may have greater preference for mixed NO_3/NH_4 nutrition and may also possess enhanced nutrient solubilization mechanisms related to root traits, but this needs to be studied in greater detail. Such studies must be conducted in real soil, not in solution culture. The sandwich techniques employed by Guy Kirk in the 1990s can be very valuable for that, but such work requires dedicated staff/graduate students. We should probably source this out to partners such as the plant nutrition group at CAU or ARIs, or try to find a Chinese student/PostDoc to apply for a CSC scholarship. This would have to be pursued now.

c. An interesting question is that of root turnover during the growing season. I'm not aware of any studies on that in aerobic rice, but it is likely that root turnover differs from that in a flooded soil, which would have significant impact on microbial processes near roots. From our work in maize we know that fine root turnover and root exudation account for the bulk of soil respiration during the growing season and there must be large differences between a flooded and an aerobic rice crop.

7. There appears to be need for a broader umbrella through which activities can be coordinated better across countries, between institutions within large countries such as China, and also between breeders and soil/water/crop scientists. In China, many different groups have started to work on aerobic rice, including many different breeding programs (and approaches), but they seem to communicate little with each other and there also seems to be little cooperation between breeders and soil and crop scientists. We see that often nowadays. Many have access to their own funding sources, but they and we could probably benefit from working more closely together, including sharing germplasm and information on cultivation practices and conducting more integrated breeding-agronomy research programs. Facilitating this is a role IRRI can play and one that could become a major, broader focus for the next phase of the STAR project.