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Aerobic Rice – responding to water scarcity

An impact assessment of the 'STAR in Asia' project

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Ruvicyn Bayot

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Impact Assessment Series 05

Aerobic Rice - responding to water scarcity

An impact assessment of the 'Developing a System of Temperate and Tropical Aerobic Rice (STAR) in Asia' project.

Deborah Templeton

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Aerobic Rice - responding to water scarcity

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Key Words: Aerobic rice; economic impact

Executive summary

Around 700 million of the world's poor live in rice-growing areas in Asia (IRRI 2008a). Rice is their main source of calories. It is also the biggest user of the available freshwater. In Asia alone, rice consumes half of the 90% freshwater diverted to agriculture (Barker *et al*., 1999). With the rapid growth of population and increasing urbanization, compounded by environmental degradation, water will soon become a scarce commodity. By 2025, over a billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world population could be under conditions of stress (UNESCO Water, 2007). If this prediction comes true, agricultural production will be affected and those who live under a dollar a day will be hurt the most.

As a response option to the looming water-scarcity problem, a new way of growing rice has been developed – the aerobic rice system, which uses drought-tolerant, input-responsive, lodging-resistant and weed-competitive varieties that can give acceptable yields using roughly half the water input of traditional lowland rice culture. The development of this technology started in China in the 1980s for breeding high-yielding rice varieties grown in non-puddled, non-flooded aerobic soil (*Han Dao*, aerobic rice variety developed by the China Agricultural University). In 2001, the International Rice Research Institute (IRRI) commenced collaboration with the China Agricultural University (CAU), the National Irrigation Administration in Tarlac (NIA-Tarlac), and the Philippine Rice Research Institute (PhilRice) to research on the appropriate crop-water-nutrient management recommendations for this system. This was done through on-station and on-farm trials and crop modelling. A long-term field experiment on the aerobic rice system was established at IRRI to assess the sustainability of the system. Also within this period, IRRI started its breeding program for tropical aerobic rice.

Funding for these collaborative research activities was very limited in the first few years. Project proposals were packaged as research on water-saving technologies, wherein aerobic rice was one of several technologies. In October 2004, the CGIAR Challenge Program on Water and Food (CPWF) started the project, Development of a System for Temperate and Tropical Aerobic Rice (STAR) in Asia. The project continued for 3.5 years, with a total budget of US$1,605,595 (approximately half from CPWF). This increase in funding added value to the aerobic rice research through the expansion of the research focus from breeding and water management to other disciplines; and through broadening the geographical focus to India, the Philippines, and to a much lesser degree to Lao PDR and Thailand. The CPWF project is the focus of this impact assessment. The Steering Committee of the CPWF recommended the ex-post impact assessment of selected CPWF projects in Phase 1. This project was selected for its potential high impact based on the Most Significant Change Stories from the Challenge Program on Water and Food projects. However, since it takes at least 5 to 10 years after the completion of a project before a technology can be fully adopted, and as this research project was completed in March 2008 (one year prior to the writing of this report), the assessment provides an estimate of potential, rather than actual, outcomes and impacts.

This impact assessment was taken following the research-to-impact pathway (output, outcome and impact). The analysis started with what the project had achieved vis-à-vis its planned outputs. The achieved intended outputs that the project reported are the following:

- Locally adapted high-yielding temperate and tropical aerobic rice varieties suited to conditions in China, Philippines and India.
- Knowledge of basic crop water and crop nutrient relationships in China, the Philippines, and India, trade-offs between water use and yield quantified, and impact on water savings assessed.
- Limited understanding of the causes and extent of factors that affect the sustainability of continuous cropping aerobic rice.
- Knowledge of the effects of seed rate and row spacing on aerobic rice yield in China, the Philippines and India, and development of initial management options and guidelines with respect to aerobic rice establishment, irrigation, weed control and fertilization.
- Information on potential target domains characterized in biophysical and socioeconomic terms.
- Capacity-building of research partners and a wide range of stakeholders in partner countries.

The scientists involved in the STAR project were responsible for the research, development, and scaling-up and scaling-out activities. They worked with farmers in the development of the technology. They set up sites for participatory varietal selection and technology demonstration to farmers and extension workers. They also conducted farmer field days and provided training to next users of the technology, e.g., seed distributors in China and irrigation managers in the Philippines.

This assessment of outcomes and impacts centers on the status of technology adoption and the factors affecting adoption. However, these cannot be fully attributed to the project because the level of technology development and promotion, as well as the driving factors, vary in each location. In the North China Plain, for example, the prime reason for growing aerobic rice is the scarcity of irrigation water for traditional lowland rice culture. Hence, it is seen as a lower-yielding but profitable alternative to lowland rice where there is inadequate water for puddling and frequent irrigation, due to physical unavailability, high cost, or policy. Aerobic rice also provides a low-risk, economic alternative to other summer crops (e.g., maize, soybean, cotton, peanuts) in large areas where flooding and waterlogging often reduce yields or even result in complete failure of summer crops. Another important characteristic of aerobic rice is that it saves irrigation water (and energy for pumping water to the field), fertilizer and labor. These savings can all be translated to a 20% reduction in production cost in comparison with lowland rice. Moreover, the low labor requirement is important in areas characterized by labor shortage due to out-migration.

At present, the area in China grown to aerobic rice is estimated at 350,000 ha, which is below the 400,000 ha baseline in 1985. However, from 2000 an increasing trend in the aerobic rice growing area is evident and which is expected to grow further largely due to increased awareness of the benefits of aerobic rice. Government policies such as subsidizing rice production are also likely to have a favorable influence on the adoption of aerobic rice technology. In the Philippines, India and elsewhere, adoption is still very low because the technology is still in the research and development stage. Therefore, the assessment of economic benefits was undertaken only for China.

Using the data and information from the project, and from the extrapolation domain analysis (Rubiano and Soto 2008), it is conservatively estimated that by 2015 the aerobic rice growing area in China will increase to over 1 million ha, and at least 15% of this area will grow aerobic rice varieties developed by the CAU.

The cultivation of aerobic rice is found to be economically viable when rice yields of 3.5 tonnes per hectare (t/ha) or more are achieved. Moreover, if the yield is 4.5 t/ha or more then the gross margin of aerobic rice is higher than that of maize and soybean grown in the same area. In addition, in irrigated systems where water is either physically or economically scarce, aerobic rice could be a profitable alternative to lowland rice.

Limiting the returns to China, and applying a 30% attribution figure, the present value of the total benefits attributable to STAR is $391 million[1]. Given that the research costs for the STAR project are in the order of $1.8 million, even if economic benefits were only ever realized in China, the net present value (NPV) of the STAR project is estimated to be $37 million over a 30-year time horizon. The corresponding benefit-cost ratio is around 21:1. Hence, even under a series of conservative assumptions, and considering the benefits in China alone, the returns to investment are significant.

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[1] In this paper $=US$.

1. Introduction

The purpose of this paper is to evaluate a Challenge Program on Water and Food (CPWF) Research and Development (R&D) project entitled 'Developing a System of Temperate and Tropical Aerobic Rice (STAR) in Asia', which commenced in October 2004 and ran for 3.5 years.

The aim of the STAR project is to develop water-efficient aerobic rice technologies. Aerobic rice is broadly defined as a production system in which input-responsive rice varieties with aerobic adaptation are grown in non-puddled, nonsaturated soils. Achieving high yields under aerobic soil conditions requires rice varieties that combine the drought-resistant characteristics of upland varieties with the high-yielding characteristics of lowland rice. In sum, the objectives of this study are to:

- Present an overview of the STAR project to obtain a detailed understanding of the collaborators and budget, the motivation for the research and project objectives, and planned outputs.
- Document the scientific achievement of the project to determine what intended and unintended outputs (including capacity built) were produced, and to provide an explanation where intended outputs were not produced .
- Assess current adoption of aerobic rice technologies, and elicit expert opinion to obtain a 'guesstimate' of future adoption to determine the expected changes at the outcome level.
- Obtain information on the use of the capacity built to assess the likelihood of sustainable research and promotion of aerobic rice technologies after the completion of the project.
- Obtain information through farmer group discussions and key informant interviews on actual and expected farm-level changes (inputs and yield) from adoption of aerobic rice technologies.
- Use the information gathered to approximate the realized and future benefits of aerobic rice technologies.
- Apply subjective measurement to attribute the benefits of aerobic rice technologies to the STAR project.

This evaluation has not considered environmental impacts, and not used any ecosystem-related criteria in the assessment. While consideration of such impacts could have added to the results of this evaluation, it was beyond the scope of this study.

The STAR project encompasses both varietal selection and management practices, and could be classified as being more adaptive in nature than basic. Nevertheless, given that adoption lags for adaptive/adoptive research are typically 5 to 10 years after the completion of such projects, it is early to undertake a full evaluation of the realized economic impact of the STAR project. Hence, this analysis relies heavily on an expert assessment of available information to obtain plausible qualitative and quantitative estimates of potential outcomes and impacts.

Also, given that the primary purpose of this paper is to assess the changes that the STAR project brought about at all levels along the research-to-impact pathway – output, outcome and impact – the analysis is undertaken within an impact pathway framework. Figure 1 shows the stylized impact pathway that was first developed by Dr. Guanghui Xie, on behalf the STAR project team, at an impact pathway workshop held in February 2006. This impact pathway was re-worked at the Yellow River Impact Pathways workshop held from 19–21 June 2007. This pathway depicts the project team's expectations in terms of outputs, practice change and impact in the Yellow River Basin.

The main limitation of Figure 1 is that it is not generic (because it was developed to articulate the impact pathway for China); and it does not explicitly include capacity built as an output. Nevertheless, it still provides a guide to the major focal points of the analysis, and to data needs and sources. Capacity building is also implicit in the model. Moreover, it helps answer the evaluation question 'Did the project follow the expected impact pathways?'

Conceptualization of the pathway depicted in Figure 1 suggests that the project team expected five main outputs: maps of characterized target domains (Box 1); adapted management practices (Box 2); adapted high-yielding aerobic rice varieties (Box 3); training models and materials (Box 4); and networks for aerobic rice (Box 5).

While the outputs depicted in Boxes 4 and 5 are not explicitly stated as planned outputs in the project proposal (sub-section 2.3), they indicate the Chinese project team's understanding that effective dissemination of the project results (both scaling-up and scaling-out) requires a change in key stakeholder's knowledge (capacity built)[2], attitudes and perceptions with regard to aerobic rice (depicted as 'Interactive learning cycle' (Oval 6).

The interactive learning cycle is implemented at the pilot research sites which were set up to not only to develop, adapt and validate the new aerobic rice technologies but to do this in partnership with the key stakeholders – scientists, government officials, irrigation managers, extension workers, farmers, etc – that the project wished to influence.

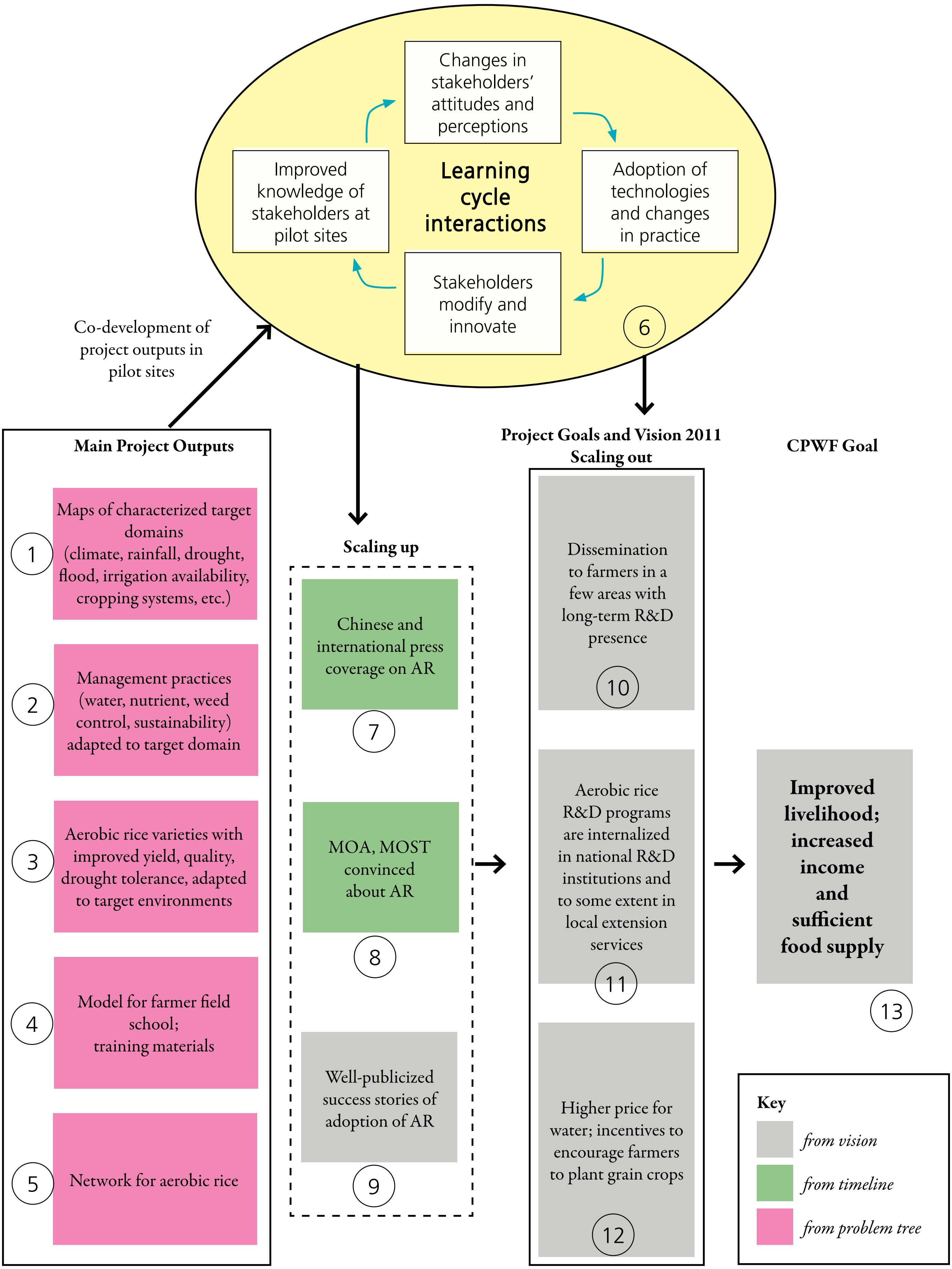
It was expected that key stakeholder participation at the pilot sites would lead to individual and collective changes in knowledge, attitudes and perceptions, experimentation, adaptation and adoption (sub-components of Oval 6) which would in turn lead to scaling-up (Boxes 7, 8 and 9) and scaling-out of aerobic rice technologies to villages and farmers beyond the target sites (Boxes 10, 11 and 12).

Widespread adoption of aerobic rice technologies would then result in the CPWF goals of improved livelihoods (increased income and sufficient food supply) being realized (Box 13).

The format of this paper is as follows. In Section 2, details of the STAR project and other aerobic rice research are provided. A short description of the methodology is presented in Section 3. The achievements of the project in terms of intended and unintended outputs are given in Section 4. In Section 5, the realized and potential adoption of aerobic rice technologies through scaling up and scaling out (outcomes) is examined. The capacity building and economic impacts of aerobic rice technologies and management practices are examined in Section 6. The conclusions are presented in Section 7.

2 Strictly speaking, the capacity built output is the knowledge and skills gained from the development and implementation of the models, training materials and the networks rather than the models, training materials and networks per se.

Figure 1. STAR Project: Impact pathway in China



2. Project details

2.1 Collaborators, research sites and budget details

During the 1980s, the CAU began breeding and selecting rice varieties that were responsive to agricultural inputs and could be grown under non-flooded conditions (Wang *et al*. 2002). In 2001, IRRI commenced collaboration with partners in China on aerobic rice research. The main purpose of that collaboration, supported by the Irrigated Rice Research Consortium (IRRC), was to quantify crop performance and water use, and to examine how alternative water and agronomic management strategies affect aerobic rice yields. In 2001 and 2002, pilot sites were established for participatory farmer research in, and development of, aerobic rice in villages in the Yellow River Basin. IRRI also started working on aerobic rice in the Philippines in the 2002 wet season with six farmers in Tarlac and four in Nueva Ecija. The activities were mostly evaluation of selected aerobic varieties under aerobic rice management in farmer fields. In India, the activities for aerobic rice started in 2003 through the Indian Agricultural Research Institute (IARI). However, overall the activities were modest and the operating budget was small.

The implementation of the STAR project in 2004 enabled acceleration of further understanding and development of aerobic rice systems in China, and the initiation of significant research on aerobic rice systems in the Philippines and India. In these countries, the target was aerobic rice systems for water-scarce irrigated areas. In addition, the STAR project enabled initiation of work to identify aerobic rice germplasm suited to favorable rain-fed environments in Lao PDR and Thailand. The work was undertaken in collaboration with IRRC (major role in dissemination) and the Consortium for Unfavorable Rice Environments (CURE) (identification and provision of drought-tolerant germplasm for testing in India, Lao PDR, the Philippines, and Thailand; see Table 1, Appendix 1). Overall, the STAR project allowed the researchers not only to increase the number of partners involved, the countries covered and the amount and type of research but also to undertake scaling-up and scaling-out activities. There were also strong links with the project on 'Developing and Disseminating Water-Saving Rice Technologies in South Asia,' supported by a grant from the Asian Development Bank (ADB). Indeed, the achievements of the research on aerobic rice under IRRC, CURE and the STAR project were important factors that led to the ADB funding a project aimed at identifying/developing potential aerobic varieties for a range of locations across South Asia.

The STAR project research sites were located in three of the CPWF's benchmark basins – Yellow River, Indo-Gangetic, and Mekong in order of level of activities – and in several basins in the Philippines (see Table 2, Appendix 1). Specifically, pilot research sites were established in China in the Liuyuankou Irrigation System in Henan (near Kaifeng); in Changping, Shangzhuang (CAU farm) and Xibeiwang villages near Beijing; and in Fengtai and Mencheng counties in Anhui Province. In India, the sites were at IARI in Delhi, and in Bulandshahar District, western Uttar Pradesh (near Delhi). In the Philippines they were located in Tarlac, Nueva Ecija and Bulacan provinces. In the Mekong Delta, the project sites were in Vientiane, Savannakhet and Champasak in Lao PDR; and in Khon Kaen, Ubon Ratchathani and Phimai in Thailand.

While China, the Philippines, India, Lao PDR and Thailand were all partner countries, as can be seen from Table 2 (Appendix 1), the greatest percentage of activities was undertaken in China (45%), followed by the Philippines (30%) and India (20%). Only 5% of the activities were undertaken in Lao PDR and Thailand combined.

The participating institutions and project team members are listed in Table 3 (see Appendix 1). As can be seen, there are seven participating research institutes that received some funding from the CPWF and a further three (all in the Philippines) that participated without any funding. In line with all the Challenge Programs (CPs), a defining characteristic of this project was the multi-institutional and multilocational nature of the research that brought together scientists from 11 institutions across six countries (IRRI being an international organization). Moreover, the research was undertaken by a strong multidisciplinary team that was able to undertake a range of activities including breeding, agroclimatology, plant nutrition, agronomy, physiology, water management, crop modelling, sociology and economics.

The STAR project was funded through the CPWF and the collaborating institutions. The budget requested from the CPWF was $884,572, with a further $721,024 (cash and in-kind) as matching funds from the collaborating institutes. In addition, further 'in-kind' contributions were made by the three non-funded partners in the Philippines. (A 6-month, 'no-cost' extension was granted to run the final project workshop and write the final report.) The funding contributions by the CPWF and other agencies (cash and in-kind) are provided in Table 4 (see Appendix 1).

2.2 Motivation for the research and project objectives

Rice is a staple food for over 70% of Asians, the majority of whom are living below the poverty line. However, even though rice is an important food source for many millions of people, it is also the single biggest user of water, requiring two to three times more water input (rain, irrigation) per unit of grain produced than the other major cereal crops, wheat and maize.

In Asia, 90% of all freshwater is used to irrigate crops; 50% for rice alone (Barker *et al*. 1999). But with growing populations, increased urbanization and environmental degradation, the supply of freshwater for all human activities is depleting. This situation is rapidly getting worse. For example, it has been estimated that by 2025, 15 million ha of irrigated rice will suffer 'physical water scarcity,' and most of the 22 million ha of irrigated dry-season rice grown in South and Southeast Asia will suffer 'economic water scarcity' (Tuong and Bouman 2002). This has serious implications for not only millions of resource-poor farmers, but also for poor rural and urban consumers who will be faced with persistent high food prices if both yield and the area sown to rice continue to trend downwards.

Most of the world's rice production comes from irrigated and rain-fed lowland rice fields. The majority is grown by transplanting seedlings into puddled soil, with the fields continuously flooded until shortly before harvest. Significant water losses can occur through seepage, percolation and evaporation, both while the crop is growing and prior to crop establishment during soaking and puddling.

With increasing water shortage, there is a need to develop technologies that can reduce these water losses. Promising technologies include water

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management practices such as intermittent irrigation (e.g., alternate wetting and drying), saturated soil culture (where soil is kept between field capacity and saturation by frequent irrigation, but water is not ponded on the field) and growing rice intensively to increase the 'crop per drop' (Bouman *et al*. 2002). However, each of these approaches still requires prolonged periods of flooding and/or wet surface soil, and so water losses remain relatively high. Consequently, to reduce water loss where water scarcity is a problem, technologies are required that enable rice to be grown in well-drained, non-puddled and nonsaturated soils, without 'ponded' water.

Recognizing the yield constraint imposed by lack of an adequate and timely supply of water, the overarching goal of the STAR project was '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' (IRRI 2004, 10). However, as alluded to above, the STAR project was not the only research project that has attempted to address, or is still addressing, the problem of water scarcity. There is a considerable amount of research on this matter in both tropical and temperate areas worldwide (IRRI 2004, 7-8), although most of this research is on technologies such as alternate wetting and drying, saturated soil culture, etc. Development of the system of aerobic rice is somewhat different because it brings together direct seeding into non-puddled soil with input-responsive varieties able to yield reasonably well with much lower water inputs than lowland rice, although maximum yields of aerobic rice are only about two-thirds of yields of flooded lowland rice.

The aerobic rice research undertaken by the CAU with IRRI since 2001 has shown that aerobic rice varieties could produce yields of up to 6 t/ha using 50% of the water used in lowland rice in the temperate rice-growing regions of north China. However, there had been little progress in the screening and selection of aerobic rice varieties for the tropics and semiarid tropics. In addition, crop-soil-water management for a sustainable production system and crop establishment recommendations were lacking, without which production and environmental sustainability could be threatened.

For example, it had already been established that a shift from continuously flooded to aerobic conditions may seriously affect soil health and weed dynamics, which can result in a significant reduction in yield in just 3 to 4 years of continuous cropping. Moreover, the environment could be adversely affected from nitrate leaching and herbicide use in aerobic systems. Finally, while the water-scarce areas were broadly recognized, there was a lack of understanding of the biophysical and socioeconomic characteristics of the prime target domains. To address these varietal and management information gaps, the specific objectives of the STAR project were to do the following:

STAR project objectives

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.

To achieve these objectives, the STAR project targeted the following:

- Irrigated areas where water scarcity restricts lowland rice production in China, the Philippines, and India (the major focus of the STAR project).
- Favorable rain-fed areas in Thailand and Lao PDR – areas where only rain-fed rice can be grown, but where rainfall is sufficiently well distributed and adequate to allow response to inputs (especially fertilizers).

While the STAR project comprises five distinct objectives, the in-country research did not encompass all of the objectives in each of the countries. Rather the project was implemented in a way to take advantage of the status of aerobic rice research in each of the target sites of interest. For example, because temperate aerobic rice varieties had already been identified and developed in China, the focus in the China target sites was on objectives 2 to 5. Indeed, by early 2000, there were reports that Chinese farmers were obtaining yields of up to 6 t/ha by growing aerobic rice varieties in water-scarce areas, under non-flooded and non-puddled conditions.

Similarly, as IRRI has an aerobic rice breeding program in the Philippines, which had identified input-responsive and lodging-resistant improved upland and hybrid varieties as potential aerobic rice cultivars prior to the STAR project, emphasis in the Philippines was again on objectives 2 to 5.

In contrast, in Thailand and Lao PDR, there had been no screening for input-responsive aerobic rice germplasm prior to the STAR project. Consequently, objective 1 on identifying and developing high-yielding aerobic rice varieties was the primary focus of research in the Thailand and Lao PDR sites. Some on-farm testing under different management methods (objective 4) was also included in Thailand.

In India, screening of aerobic varieties was initiated in 2002 by IRRI through CURE. As part of the STAR project, the varietal screening continued and included combined variety screening with water and seed rate experiments (objectives 2 and 4).

2.3 Planned outputs

As stated in the project proposal the intended outputs included the following components of aerobic rice technology:

1. First generation of tropical aerobic rice germplasm with high yield potential, and improved aerobic rice varieties in China.
2. Basic crop water and crop nutrient relations understood.
3. Prototype aerobic rice production systems focusing on water and nutrient management, crop establishment and weed control, and crop rotations.
4. Key sustainability and environmental impact indicators identified.
5. Trade-offs between water use and yield quantified, and impact on water savings assessed.
6. Potential target domains characterized in biophysical and socioeconomic terms.

The proposed research activities and methodologies to achieve the outputs included pot and on-station controlled experiments for varietal selection, breeding, crop-nutrient-management analysis and nematode ecology. On-farm participatory research was also planned to develop practical technologies for aerobic crop establishment, weed control, and crop rotation.

Farmer surveys were planned to examine factors affecting adoption, and the use of GIS tools was proposed to help determine domains likely to be suited to aerobic rice technologies in terms of soil type, climate, hydrology and socioeconomic conditions.

Simulation modelling was also intended to extrapolate experimental findings to wider environments (soil, weather, and hydrology), and to compute irrigation water requirements and yield levels under different irrigation management scenarios.

3. Methodology

The assessment was carried out through a review of project documents and publications, and documents from other related projects; key-informant interviews; and site visits. It started in February 2008, and was completed one year later.

Key data and information were taken from the STAR project's completion report, from the economic assessment of aerobic rice in Anhui Province commissioned to Prof. Ding Shijun, and extrapolation domain study by Drs. Jorge Rubiano and Victor Soto. Other information was obtained from personal communications with Prof. Wang Huaqi (CAU-Beijing), Dr. Boru Douthwaite (CPWF Impact Assessment), Dr. Elizabeth Humphreys (CPWF Theme 1), Dr. Rubenito Lampayan (IRRI), Dr. Vicente Vicmudo and Mr. Armilito Lacatoen (NIA-Tarlac), and Dr. Junel Soriano (BASC).

Additional data and information were obtained through focus group discussions with farmers in Tarlac and Bulacan provinces in the Philippines, and in Anhui and Henan provinces in China. The farmers were selected by the STAR project members. The Filipino farmers were farmer-cooperators involved in farmers field trials. They grow both aerobic and traditional rice varieties. The Chinese farmers were aerobic rice farmers who had been introduced to the aerobic rice varieties through field demonstration, participatory variety selection, and seed distributors.

Other informants in China were government officials (county and township levels), staff from the Agricultural Technology Extension Station (ATES), rice millers, and seed distributors. In Shangtang township (in Fengtai County), the assessment group interviewed farmers randomly selected from the people present in the market place. They were grouped into lowland rice farmers, aerobic rice farmers, and farmers growing both lowland rice and aerobic rice.

The sites visited represented the target domains for aerobic rice cultivation:

- *Canarem, Victoria, Tarlac, the Philippines* – aerobic rice was planted in the fields located at the tail end of the gravity irrigation system, managed by the National Irrigation Administration in Tarlac. Farmers use pumps to get groundwater to supplement irrigation. Their main concern was not the actual lack of water but the cost of fuel used to supply irrigation to their fields.

- *San Ildefonso, Bulacan* – aerobic rice was planted in farmers' rain-fed fields. Supplementary irrigation was taken from small water impounding systems.

- *North China Plain* – this is one of the important agricultural regions in China. It is characterized by alternate drought and flood events, and irrigation is from canal systems and groundwater.

4. Project outputs

4.1 Achieved intended outputs

Determining the achievements of an R&D project at the output level is generally relatively straightforward. However, in the present case, it was not a trivial task because the write-up of the results in the final project document is not directly comparable to the description of the proposed outputs in the project proposal. As such, the description of the outputs provided below follows the final report (IRRI 2008b), while in Table 5 (see Appendix 1) this information is used to assess whether the proposed outputs were achieved as specified in the project proposal (IRRI 2004, 15).

The actual outputs from the STAR project, as documented in the final report, include:

a) locally adapted high-yielding temperate and tropical aerobic rice varieties suited to conditions in China, the Philippines and India;
b) knowledge of basic crop-water and crop-nutrient relationships in China, the Philippines and India;
c) limited understanding of the causes and extent of factors that affect the sustainability of continuous cropping of aerobic rice;
d) knowledge of the effects of seed rate and row spacing on aerobic rice yields in China, the Philippines and India; and,
e) limited information on potential target domains characterized in biophysical and socio-economic terms.

The key outputs from 3.5 years of project operation are as follows:

a) Locally adapted high-yielding temperate and tropical aerobic rice varieties suited to conditions in China, the Philippines and India (*Objective 1, Output 1*)

Selection of aerobic rice varieties involved the evaluation of advanced breeding lines and existing varieties in all countries, on-station trials, and on-farm participatory trials in India, the Philippines and Thailand. In sum, while the STAR project did not breed new rice varieties, it confirmed that aerobic rice varieties can yield 4-6 t/ha using significantly less input water than lowland rice (see below). Moreover, experiments undertaken showed that, even though aerobic rice is water-efficient, it can also withstand occasional flooding.

The STAR project identified three varieties suitable for aerobic rice production in China (HD277, HD297 and HD502); a further three in the Philippines (PSBRc9 [Apo], UPLRI5, and PSBRc80); and four varieties in India (Pusa Rice Hybrid 10, Proagro6111 (hybrid), Pusa834 and IR55423-01 [Apo1]). All these varieties are available without restriction through private seed companies or national seed distribution channels. However, yields of aerobic rice in farmers' fields in China were usually only around 3-4 t/ha while researchers' yields were 5-6 t/ha. Compared with traditional lowland rice culture in China, India and the Philippines, the maximum yields of aerobic rice were only about two-thirds of achievable yields. While promising breeding lines were identified in Lao PDR and Thailand, further breeding is required before suitable lines can be determined and released.

b) Knowledge of basic crop-water and crop-nutrient relationships in China, the Philippines and India (*Objective 2, Output 2*) and trade-offs between water use and yield quantified, and impact on water savings assessed (*Objective 2, Output 5*)

During the life of the project, water and nutrient dynamics were examined through a number of on-station and in-field experiments conducted in several sites in China, the Philippines and India. In addition, further insights were obtained through simulation modelling for China. Nitrogen and row-spacing experiments were undertaken in the Philippines and N, P and K experiments were carried out in China and Lao PDR.

In terms of increased understanding, elucidation of the difference in the relationships between input water and yield for aerobic and lowland rice was important because it helped define, in terms of water availability, which production system (aerobic or irrigated lowland) is likely to optimize yield for a given water availability/scarcity. It also highlights the usefulness of generating water-responsive data for other regions to determine where aerobic rice systems might be beneficial.

c) Limited understanding of the causes and extent of factors that affect the sustainability of continuous cropping aerobic rice (*Objective 3, Output 4*)

Earlier research in Japan, the Philippines and Brazil has shown that continuous monocropping of upland rice varieties results in declining yield (Nishizawa *et al*. 1971; George *et al*. 2002; Pinheiro *et al*. 2006). While possible causes for this are believed to be a build up of nematodes (Nishizawa *et al*. 1971), soil pathogens, toxic substances from root residues (Nishio and Kusano 1975) or a decline in nutrient availability (Lin *et al*., 2002), to date the evidence is inconclusive.

Research activities within the STAR project were undertaken to see if the same yield decline would occur in continuously cropped aerobic rice and to determine the causes of any documented decline. The pot and field experiments designed to determine the causes and severity of yield decline in continuous aerobic cropping systems were largely undertaken at IRRI in Los Baños, the Philippines (both prior to, and as part of, the STAR project). The variety Apo (PSBRc9) was used for all experiments. The yield effects from continuous cropping were very clear – yield declined by 2.5 t/ha by the seventh season. Nematode counts were found to be higher in aerobic fields than in the continuously flooded fields, although no correlation was found between nematode counts and grain yield.

The same research also showed that yield decline could be reversed through crop management practices that incorporated crop rotations, fallowing and/or flooding. The results of the research showed that flooding for three consecutive seasons or fallowing for two seasons was equally effective in restoring aerobic rice yields but cropping with upland crops such as soybeans, sweet potatoes or maize was even more effective. On the other hand, the application of micronutrients such as P and K had no effect but crop growth was consistently improved with the application of N fertilizer. The research also showed that after the tenth season yields increased spontaneously suggesting a self-regenerating mechanism – although this is little understood.

In the Philippines, there were two cases of immediate yield collapse (first crop), which may have been due to high pH as a result of alkaline irrigation water and/or the type of nitrogen fertilizer.

Despite the research undertaken at IRRI, by the end of the STAR project, the precise reasons for, and extent of, yield decline in continuous cropping aerobic rice and yield collapse were still not fully understood. Hence, further research is required to fully identify key sustainability and environmental impacts, and to develop management practices for sustainable cropping systems with aerobic rice. Meantime, it is recommended that consecutive crops of aerobic rice should not be grown on the same field.

d) Knowledge of the effects of seed rate and row spacing on aerobic rice yields in China, the Philippines and India (*Objective 4 and part of Output 3*) and initial management options and guidelines with respect to aerobic rice establishment, irrigation, weed control and fertilization (*Objective 4, Output 3*)

Multifactor experiments were undertaken to determine the effects of seed rate and row spacing under different water and N regimes on the yield of aerobic rice. These experiments were limited to China (seed rate and row spacing) and India (seed rate) and the Philippines (row spacing).

The main conclusions to be drawn from the experiments are that the yields of dry-seeded aerobic rice varieties (Apo in the Philippines and HD297 in China) are not very responsive to row spacing between 25 and 35 cm or seed rates between 60 and 135 kg/ha. In India, the yield of Pusa hybrid rice variety was unresponsive to seed rates between 40 and 80 kg/ha but fell substantially when the seed rate was below 40 kg/ha.

It was suggested that the relative unresponsiveness to row spacing and seed rates will provide farmers with some flexibility; while higher seed rates may suppress weed growth, it will cost more.

The STAR project provided some initial management options and guidelines for aerobic rice production. These covered crop establishment methods, seeding rates, row spacing, irrigation requirements and fertilizer application (quantity and timing).

For example, it is suggested that before seeding, the plot should be ploughed and harrowed to obtain smooth seed beds. Seeds can then be dry seeded at a depth of 1 to 2 cm in clay soils and 3 to 4 cm in loamy soils. (Alternatively, seedlings can be transplanted into saturated clay soils that are kept wet for a few days after transplanting.)

While the experiments did not show that yields are reasonably responsive to seed rate or row spacing, it is suggested that optimal seed rates are around 70-90 kg/ha and row spacing could be in the order of 25-35 cm. If grown in the dry season, the prime irrigation recommendations are to apply 30 mm after sowing to promote emergence and then, depending on rainfall quantity and pattern, irrigate around flowering.

As aerobic rice is not grown in permanently flooded soils, weeds can be a problem. To control weeds a pre- and/or post-emergence herbicide (plus some manual or mechanical weeding) is recommended.

Fertilizer requirements will depend on the level of nutrients already available to the crop. Leaf color charts (LCC) can be used to determine site-specific nitrogen (N) needs.

In the absence of LCC and the knowledge and skills in site-specific nutrient management, a good starting point recommended is around 70-90 kg N/ha – with adjustments made as necessary. The nitrogen should then be split into three applications. In the case of direct seeding, the first application should be applied 10-15 days after emergence, the second at tillering and the third at panicle initiation. It may also be necessary to apply phosphorus (P) and zinc (Zn) on high pH soils.

Photo: R. Bayot

e) Information on potential target domains characterized in biophysical and socioeconomic terms (*Objective 5, Output 6*)

Target domain analysis was undertaken to determine the biophysical and socioeconomic suitability of the aerobic rice technology beyond the research sites. The main focus of the domain analysis was China.

The components of the domain analysis undertaken solely in China included field experiments (Changping, Beijing), variety zoning (whole country), crop modelling and linking with GIS (Beijing, Tianjin, Shandong, Hebei, Henan), and household surveys (Kaifeng, Tianjin, Shandong, Hebei, Henan) (Ding *et al.*, 2008; Moya *et al.* 2008).

Global extrapolation domain analysis was also initiated by the CPWF Basin Focal Project based on site similarity analysis (poverty, climate) with the project pilot sites in all project countries except the Philippines, and taking into account slope, presence of irrigated lands and presence of rice growing – although at the time of the final report this work was still underway (Rubiano and Soto 2008).

The main findings of this research were the following:

- In northern China, the target domains are areas where water availability (with and without irrigation) is 400 to 900 mm during the cropping season, with HD297 and HD502 (among others) being the most suitable varieties.
- Yields of 5 to 6 t/ha are attainable in the central part of the Yellow River Basin (Kaifeng area), and in most of the North China Plain.

- In these areas of China, farmers currently obtain 3 to 4 t/ha of aerobic rice, providing them with returns largely comparable to those from upland crops such as maize and soybean. If farmers could achieve aerobic rice yields of 6 t/ha, then aerobic rice would be more profitable than the upland crops. The respondents from farmer surveys stated that the main advantages of growing aerobic rice are being able to grow rice, the ease of establishment, low labor requirements and good eating quality. The main disadvantages highlighted by the respondents are low yield, difficulty in controlling weeds, insufficient support from extension agencies and limited market acceptance (despite the good eating quality).

- Extrapolation domain analysis at a 70% probability of finding similar socioeconomic and climatic conditions to the pilot sites in Asia, Africa and Latin America suggests that aerobic rice can have a large impact in India, followed by China, Thailand and Myanmar (Rubiano and Soto 2008).

4.2 Achieved unintended outputs

The STAR project is a prime example of an R&D project within which capacity-building was an integral part of the project activities. Much of the capacity-building was done through 'learning-by-doing.' This hands-on experience was an important part of training for the 22 graduate and undergraduate students who were directly involved in the project.[3] Several graduate students and scientists from project partners in local research institutions were also trained on-the-job at IRRI in data analysis, crop modelling and writing papers for international journals. In addition, aerobic rice was a component of many training courses on water management. These training courses were facilitated by the STAR project and the Water Working Group of the IRRC. Most of the courses were undertaken in the Philippines although they were also undertaken in Bangladesh, Myanmar and Vietnam. The course topics included applied science, water management and extension. As such, the courses were not designed for farmers but rather for farmer intermediaries who could, in turn, pass on some of their new knowledge, understanding and skills to the farmers. Trainees included staff from institutes, universities, extension agencies and irrigation system administrators. It is estimated that altogether 1,589 attendees received training on aerobic rice from 2004 to 2008 (IRRI 2008b).

Therefore, even if not explicitly stated as an output in the final project report, a significant achievement of the STAR project is capacity built. This was recognized at the impact pathway workshops held in February 2006 and June 2007. Relative to the level of capacity prior to the commencement of the project, the changes in capacity that can be directly attributed to the project's activities cover four main categories as follows:

- Development of skills, knowledge and confidence of the researchers, extension agents, farmers and others, in the partner countries including networks or linkages of researchers formed.
- Development of the stock of knowledge available to researchers within the organization and/or the wider research community.
- Development of research tools such as methodologies, databases, models (e.g., parameterization and calibration of the ORYZA crop growth simulation model for aerobic rice and the IMPACT-WATER Model, extrapolation domain analysis by the combined use of GIS and crop model simulations).

[3] Of the 22 students, 14 were enrolled in CAU; three in Central Luzon State University (Philippines); two at the University of the Philippines, Los Baños; two at Wageningen University (Netherlands); and one at the Universita degli Studi di Firenze (Italy).

- Organizational capacity to undertake research efficiently and effectively and attract research funding, and significant organizational linkages and networks formed.

In China, the knowledge and skills of scientists at the CAU gained through the STAR project enabled them to conduct rigorous research (including undertaking a multidisciplinary approach to aerobic rice research), collect and analyze scientific data and write up the results. The scientists were also exposed to the concept of being impact-focused – that is, thinking beyond the life of the project – at the impact pathways workshops held in Vientiane in February 2006 and June 2007. Exposure to GIS, simulation modelling and socioeconomic indicators increased awareness of the suitability of aerobic rice technologies beyond the targeted project sites. In addition, links between the CAU scientists and scientists in other countries were established through formal and informal networks. These networks not only further increased the knowledge and skills of the CAU scientists but also gave them the opportunity to pass on their experiences with other scientists through the networks and at international conferences and workshops. Overall, the stock of knowledge available to researchers within the CAU and to the wider research community increased as evident from the number of key research papers published in a number of international journals (e.g., Appendix 2).

All of this culminated in the CAU having a reputation, both nationally and internationally, for undertaking relevant and robust research on aerobic rice technologies. This enhanced their ability to attract further funding for aerobic rice research from both national and international sources. For example, the CAU is receiving $50,000 (CNY350,000) as part of the $1.5 million (CNY10 million) Ministry of Agriculture-funded project entitled 'Creating new technology platforms to discover profitable genes in crops' (2006-2010). The role of the CAU in this project is to develop drought-tolerant rice varieties and discover relevant new genes in rice. In addition, the CAU is a collaborator in a $2.2 million (€1.7 million) European Union (EU) project entitled 'Developing drought-resistant cereals to support efficient water use in the Mediterranean area (Europe Union-FP6 2006~2008).' As part of this project, the CAU is receiving around $130,000 (€100,000) to develop drought-tolerant rice varieties and identify germplasm field drought tolerance for the Mediterranean area and partners.

Capacity built was also a significant output in the Philippines. The capacity of scientists and/or students at PhilRice, CLSU, BASC and BSWM to undertake aerobic rice research was increased. For example, BASC added an aerobic rice component to their applied research program focusing on crop management and varietal selection. BASC, with BSWM, became successful in applying for national R&D grants (IRRI 2008b).

The incorporation of aerobic rice in the applied sciences programs and extension activities of the various partner institutes, and the ability of the institutes to obtain further funding for aerobic rice research provides a strong indicator that the knowledge and technical and management skills of the individuals and the institutes as a whole were increased as a direct result of their involvement in the STAR project.

In addition to the capacity built through formal research and education platforms, national and local partners in both China and the Philippines facilitated demonstration and training workshops aimed at building the awareness, knowledge and skills of next and final users of aerobic rice technologies. In China, the CAU organized large-scale training and demonstration sessions in Fengtai, Mencheng, Kaifeng, Funan and Fengyan with a minimum of 50 to 100 participants attending each training activity. For example, in September 2005 an aerobic rice demonstration and training session was held in Fengtai County. The 150 participants came from seven counties and consisted of farmers, technicians from extension stations, managers of seed companies and rice mills, and government officials. In the Philippines, the irrigation managers (NIA-Tarlac), extension workers and farmers learnt about locality-specific promising aerobic rice varieties and management strategies through the capacity-building activities of the project. Also, BASC and BSWM jointly initiated numerous applied research and demonstration activities passing on their knowledge on aerobic rice technologies to farmer groups. Farmer training, demonstrations and field days were funded through local government units and village leaders.

An indicator of the capacity built from demonstrations and training workshops is the results of post-training competency tests. However, these were not undertaken so that a direct measure of the degree of any increase in knowledge and skills is not available. Nevertheless, given the number and background of the participants, it would be reasonable to expect that the capacity of the participants of the aerobic rice demonstrations, meetings and field days would have increased.

Photo: B. Bouman

5. Adoption

Clearly, outputs will not translate into impact unless they are used. This section describes how the outputs set out in the previous section are being used by the next (researchers, irrigation system managers, and farmer intermediaries) and final users (farmers). The discussion examines what has happened to date, as well as making an assessment of future adoption. However, it should be noted that while all participating countries were covered in sections 1 to 3, in the remaining sections the focus is on China and the Philippines. The reason for this is threefold:

- As shown in Table 2 (see Appendix 1), 75% of the project activities were conducted in China (45%) and the Philippines (30%).
- Aerobic rice technologies are more advanced in China and the Philippines than in the other project sites - India, Lao PDR and Thailand.
- Due to time and resource constraints, the 'ground-truthing' activities undertaken as part of this assessment were limited to China and the Philippines (see Table 6, Appendix 1).

5.1 Capacity Utilization

The knowledge and skills that the researchers in China and the Philippines gained through their participation in the STAR project led to numerous practice changes. In China, one of the most significant changes was the type of aerobic research undertaken at the CAU. Prior to being involved in the STAR project, aerobic rice research was primarily undertaken by plant breeders. It is now undertaken by a multidisciplinary team including hydrologists, agronomists, soil scientist, and crop modelers joining the plant breeders to undertake collaborative research with the common goal of developing locally adaptive aerobic rice varieties.

Research was also undertaken in the farmer fields, rather than just at the research station, and the scientists became actively involved in farmer participatory field monitoring and socioeconomic surveys. The CAU gained an international perspective on the type and extent of the aerobic rice research being undertaken, and methods being used because of their exposure to the international aerobic rice community, through the networks established by the STAR project and attendance and participation in international fora. This exposure influenced the design of their experiments. In particular, the need for appropriate crop management practices to be developed and 'packaged' with the promising aerobic rice varieties, and the benefits of undertaking long-term experiments, now feature in the research being undertaken by the aerobic rice research team at the CAU.

In the Philippines, the original partners engaged in the STAR project were PhilRice and NIA-Tarlac. They used the knowledge and skills gained to organize and participate in numerous national training programs and workshops on aerobic rice which attracted other institutes to become nonfunded partners in the STAR project (see bottom part of Table 3, Appendix 1). These partners then used some of their knowledge and skills in their research, teaching, training and/or extension activities (as mentioned above).

5.2 Factors Affecting Adoption

Past experience shows that even if an R&D project achieves the planned outputs, it does not necessarily follow that they will be adopted by the intended users. Broadly speaking, there are a number of special challenges to adoption, and hence impact, as follows:

- The requirements of the intended users need to be clearly understood.
- Change is often complex and depends on numerous factors outside the control of the researchers.
- Researchers have little control over the final processes or steps towards impact as someone else is usually responsible for working with the final users.
- Adoption and impact often occur long after the project is finished.

The key informant interviews undertaken in both China (October 2008) and the Philippines (March 2008) suggest that all these challenges were considered in the design and implementation of the STAR project.

Meeting the needs of farmers

In China, the areas visited for the key informant interviews were typically both drought- and flood-prone (Table 7). In line with these climatic conditions, the prime reason for growing aerobic rice (as stated by government officials, farmer intermediaries, and the farmers themselves) is that aerobic rice is both drought- and waterlogging-resistant (see Table 7, Appendix 1).

The key informants stated that there had been significant crop losses in the past with other summer crops such as maize and soybean due to waterlogging. As a result of these yield losses, aerobic rice is seen as either a profitable alternative to other summer crops or as a security crop, ensuring farmers receive some income when other crops are affected by waterlogging. However, yield is still below that of paddy rice and appropriate water management techniques are not always known or achievable.

Another important characteristic of aerobic rice technology that meets the requirements of farmers is that management is relatively simple, saving on labor inputs. This is important in an area now characterized by labor shortage due to out-migration. In fact, Ding *et al.* (2008) found that labor saving was the most important attribute of aerobic rice systems for farmers.

Interestingly, some key informants also stated that another benefit of growing aerobic rice is that the yield is stable even after growing aerobic rice in the same field for 5 consecutive years. However, farmers in Shangtang township in Fengtai County mentioned there was a yield decline over consecutive years when growing one variety in the same field, and it seemed quite significant. They reported the need for variety improvement to help abate the problem of yield decline.

While weeds once inhibited adoption, according to the Director of the Xincai Agriculture and Extension Service and some farmers, weed control is no longer a major issue as good post-emergence herbicides are now available (Table 7, Appendix 1). It was stated that the increased and/or renewed interest in aerobic rice was due to the availability of the herbicides and the increase in farmer skills in chemical weed control. Nevertheless, weeds were still stated as being an invasive problem by a number of the key informants.

The farmers also stated they were happy with the eating quality of aerobic rice in general, although there is a strong relationship between varietal choice and whether or not the rice is an indica or a japonica. For example, the CAU varieties are japonicas, which are generally preferred in the north. In the south, both japonica and indica varieties are accepted. However, as can be seen from Table 7, Appendix 1, preference can be localized. In Fengtai County, the farmers grow japonicas (Zhonghan 209, HD277, HD 502); in Funan County japonicas (HD209, 277 and 502) and indicas (Lvhan1); and in Xincai County indicas are the preferred variety (e.g., Xinhan1, 2 and Lvhan1). In Tarlac and Bulacan provinces in the Philippines, farmers have shown considerable interest in aerobic rice as a summer crop as it addresses some of their pressing needs. In short, this interest is largely driven by the four-fold increase in the cost of deep- and shallow-well irrigation (due to the increase in fuel prices at the time of the interviews) and the need to increase farm income in rain-fed areas by providing farmers with a means of producing two crops per year.

Another factor affecting the farmers' decision to grow aerobic rice is soil quality. While the farmers will also grow maize in the dry season, it can only be grown on the portion of their land that has sandy soil. In addition to maize production, other upland crops that are grown include sweet potatoes, peanuts and vegetables. However, these upland crops cannot be produced on a large scale because of the lack of processing, transportation and retail facilities.

Change depends on factors outside the researchers' control

There are many factors outside the control of researchers that will affect adoption of the results of agricultural research. One of the highest-order factors is a country's political environment.

In both China and the Philippines, the current agricultural agenda is one of strongly encouraging grain production. This is not surprising given the recent 'food price crisis.' The shift in political will is particularly evident in China. Prior to 2004, grain production was subject to an output tax; inputs used for grain production are now subsidized and a per unit production amount for growing improved varieties of the major grain crops (e.g., wheat, maize and rice) is paid by the government into the farmers' accounts. Farmers now receive $175-200/ha worth of output payments and input subsidies for growing grain crops. In the Philippines, the government is not only subsidizing Bt corn seeds but is also actively promoting rice production. As a result of these payments, the profitability of growing aerobic rice in the dry season is increased, which will have a positive influence on adoption.

Another factor outside the control of the researchers is the out-migration of labor from rural areas. This seems to be of particular concern in China where the average size of the household is smaller than in the Philippines. As stated above, the fact that aerobic rice requires less labor than lowland rice and other summer crops means that it is well suited to this change in demographics.

Oil prices can also affect adoption of aerobic rice. This is particularly true in the areas visited in the Philippines. Farmers in Tarlac and Bulacan are interested in growing aerobic rice because of the fourfold increase in irrigation costs due to the rise in the price of oil (at the time of the interviews). One could surmise from this that the reverse could also be true: aerobic rice growers may 'switch-back' to lowland rice if the economic constraints to irrigation are eased. Local weather conditions may also play roles in promoting adoption. The occurrence of alternating flood-drought conditions may be one reason why farmers grow aerobic rice in Anhui and Henan.

Someone else is usually responsible for working with the final users

A major downfall of some R&D projects is the failure to recognize and account for the fact that others may be responsible for ensuring the project results are passed on to the final users. This does not apply to the STAR project, which actively undertook communication and dissemination activities, including a large number of training demonstrations, through the collaborations and the networks formed. These activities all served to pass on the results of the STAR project to a wide-ranging group of next users.

In China, scientists at the CAU were not only responsible for undertaking aerobic rice research but also became involved in both scaling-up and scaling-out activities. As part of these activities, managers of seed companies and seed distributors were invited to the field days and training demonstrations. This was important because agricultural technologies are often disseminated through the seed delivery system in China. While public extension stations are part of the seed system, it is the private sector – private seed companies and local seed dealers – that is the main channel for the promotion and spread of new technologies such as aerobic rice. Results from the farm-level surveys undertaken in 2007 indicate that local seed dealers supplied 73% of the surveyed farmers with aerobic rice seeds (Ding *et al.* 2008).

Seed exchanges by farmers also played an important role, with 19% of farmers obtaining aerobic rice seeds through farmer-to-farmer exchanges (Ding *et al*. 2008). These results were confirmed during the key informant interviews undertaken in October 2008, which showed that private seed companies and distributors provided farmers with new locally adapted aerobic rice varieties and information on management strategies (Table 7, Appendix 1).

However, as pointed out by Ding *et al.* (2008), while private companies have a financial incentive to promote new technologies, in the case of aerobic rice they may not have the capacity to provide intensive training and/or set up demonstration sites. Therefore, there is a need for the public sector to be involved in these activities. In China, while the involvement of the public sector in the extension of aerobic rice has been limited, there has been some government support through the National Program of Aerobic Rice Regional Trials, which is ongoing.

In contrast to China, where most of the dissemination activities are done through private seed companies, in the Philippines, the various project collaborators are involved in the adaptive and/or participatory research, training and dissemination. The means of technology dissemination is largely through farmer participatory on-farm demonstrations, farmer field schools and trained technicians. There is also substantial local government support in the targeted provinces. In addition, the National Irrigation Authority is actively passing on information on the benefits of growing aerobic rice to the farmers within the agricultural areas in Tarlac.

5.3 Current Adoption of Aerobic Rice

China

As previously stated, aerobic rice research started in China over 25 years ago. By 1985, the area of aerobic rice growing there was around 400,000 ha (Table 8). Of this, 12% of the cultivated area was sown to varieties developed by the CAU. By 1995, this extent had fallen to 266,000 ha. The reason for this was that there were no new aerobic rice varieties released and the increased supply of irrigated lowland rice during this period led to a fall in the price of rice in both absolute terms and relative to other crops.

The release of new varieties was reinforced by the National Program on Aerobic Rice Regional Trials implemented in 2000. The main objective of this program was to identify and release promising elite varieties to farmers legally. There are 69 sites for breeding trials. In this program, HD297 and HD277 are used as check varieties. The main objective of the regional trials is to increase aerobic rice yields. The CAU contribution to the country-wide adoption of aerobic rice rose from 10% in 2005 to 15% in 2008. This increase can be attributed to the STAR project.

Table 8. Area sown to aerobic rice: 1985 to 2008

Year	Total area '000 ha	Contribution of CAU		CAU key cultivars used
		'000 ha	%	
1985	400	50	12	Qinai
1995	266	7	3	Qinai, Handao2
2000	300	60	20	HD277, 297
2005	333	33	10	HD277, 297, 502
2008	350	53	15	HD277, 297, 502

Source: Prof. Wang, CAU 2008[4], pers. comm.

During 2003-2005, 35 new aerobic rice varieties were released bringing the total to 58 varieties nation-wide. Five of the certified varieties (HD9, HD65, HD277, HD297, HD502) released in 2003 were from the CAU, with the sixth CAU variety (HD271) released in 2005. While the STAR project did not start until October 2004 (after the release of some of these varieties), it provided evidence that the CAU varieties, such as HD227, HD297 and HD502, out-yield lowland rice varieties under water scarcity. This confirmation served to increase confidence in promoting aerobic rice.

In addition to varietal selection, and as a result of the STAR project, the CAU also undertakes adaptive management research for aerobic rice systems. The technologies include direct dry seeding, seed coating, and management of water, weeds and nutrients. The CAU also works closely with a number of private seed companies and local seed distributors, with the aim of accelerating adoption of aerobic rice in China.

4 Prof. Wang Huaqi leads the aerobic rice team at the CAU. He has been actively engaged in aerobic rice research in China for around 30 years.

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The increased research and dissemination effort since the start of the STAR project, combined with the change in the government policy on grain production and the increase in out-migration of labor, appears to have accelerated the rate of adoption in recent years. Ding *et al.* (2008) point out that while adoption of aerobic rice in Funan County dates back to the 1990s, aerobic rice was not adopted in Fengtai and Yingshang until 2003 with over 60% of aerobic rice farmers not growing aerobic rice until 2006.

By 2008, the total area grown to aerobic rice in China was still 50,000 ha below the 1985 area. Nevertheless, the key informant interviews held in the Yellow-Huai River Basin in October 2008 indicate that interest in aerobic rice had increased markedly over the last 12 months, largely due to increased awareness of the benefits of growing aerobic rice, a greater understanding of appropriate management techniques, and the favorable government policies for growing grain crops (Prof. Wang, CAU 2008 pers. comm.; key informant interviews 2008).[5] In fact, in some instances farmers have stated that the reason they have not been able to grow aerobic rice is the non-availability of seeds. The increased demand for aerobic rice seed in some locations is reflected in the increased price of aerobic rice seed from the previous year and the increase in the area used for seed production in 2008 (e.g., in Xincai County – see Table 7, Appendix 1).

The Philippines

In the Philippines, there has been very little adoption of aerobic rice varieties to date, despite the

5 Prof. Ding Shijun, who was responsible for the household surveys undertaken in 2007, acted as a translator during the key informant interviews in October 2008. He also commented on the marked increase in the use of, and interest in, aerobic rice in just 12 months (Ding 2008, pers. comm.).

considerable interest shown by farmers during the key informant interviews undertaken in March 2008. The main reason for the lack of adoption is that further varietal and management adaptive research is required to ensure that the yield potential of the varieties and management package delivered to the farmers is largely attainable in the farmer fields.

For example, in 2005, six demonstration farms were set up in Bulacan with almost 50 farmers growing aerobic rice varieties. However, the farmers did this without fully understanding the correct water and nutrient management strategies. As a result, the average yield was 2-3 t/ha rather than 4 t/ha. Subsequently, the National Economic and Development Authority Region III (NEDA-Region III) initiated a training and extension proposal (including the production of aerobic rice seed).

In April 2008, two demonstration farms in six municipalities in rain-fed areas of Bulacan were being set up (1.5 ha at each site). This initiative has the support of the Bulacan Provincial Office with BASC training technicians.

The training and extension are conducted through the farmer field schools (FFS) and covers land preparation through to harvesting. Information on aerobic rice will be passed on to the farmers via FFS and the trained technicians.

While at the time of the key informant interviews it was stated that in 5 years there will be a 50% adoption of aerobic rice varieties in the target areas (Dr. Junel Soriano 2008 pers. comm.), this statement was made when oil prices reached record highs.

Now that there has been a substantial fall in the price of oil, adoption may not be as high as originally predicted – at least not in the short term.

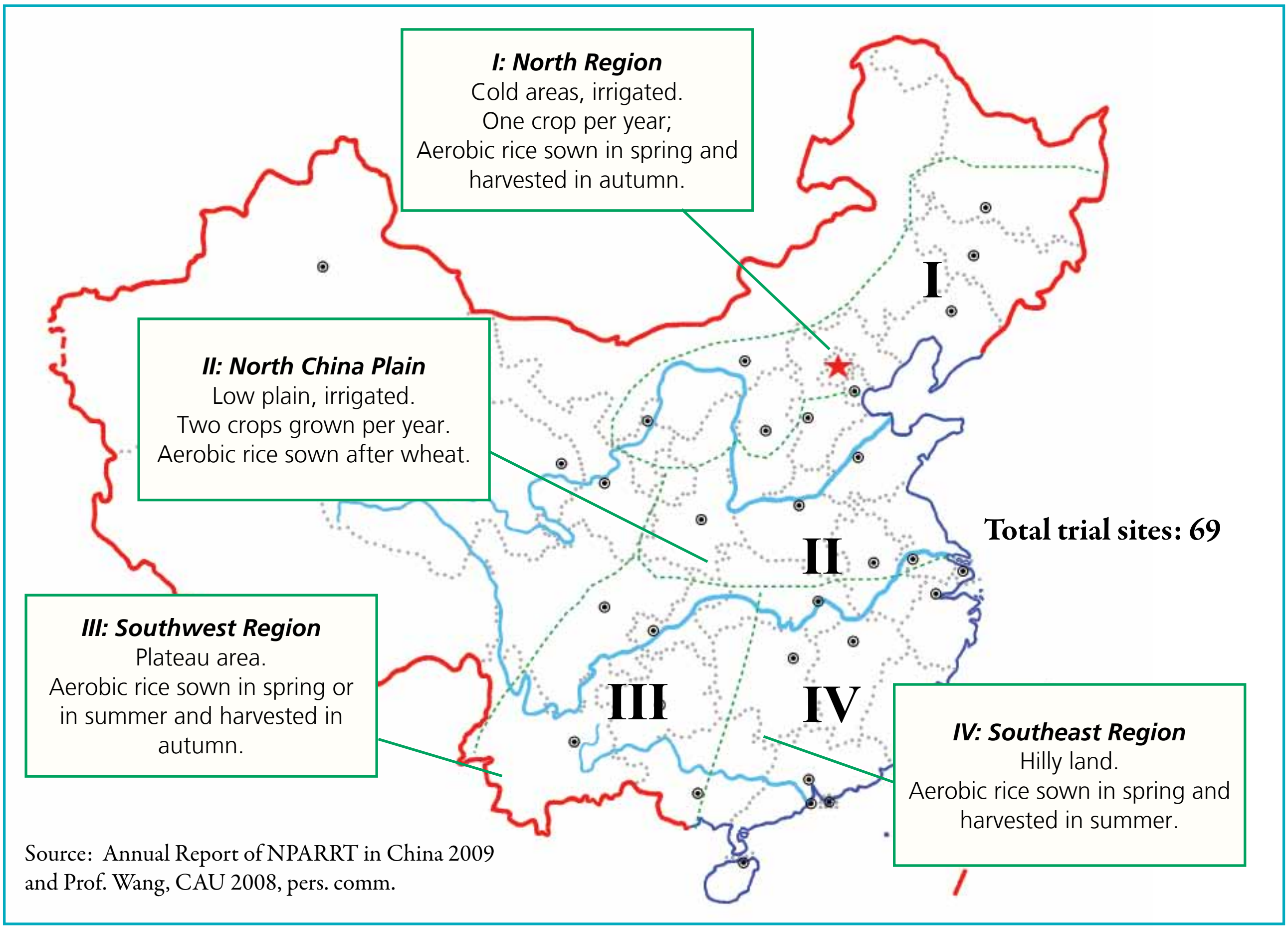
5.4 Future Adoption of Aerobic Rice

While information from the key informant interviews indicates that farmer interest in, and uptake of, aerobic rice are increasing, determining an adoption profile is not an easy task and requires a significant degree of subjective assessment. However, the plausibility of the assessment can be increased by considering all the relevant information from, for example, secondary data, the key informant interviews, project reports and related research, and previous household surveys. In the present case, an important first step is to consider the agroclimatic domains where aerobic rice could not only be grown but would also have a comparative advantage over either lowland rice or upland (summer) crops. Very broadly, these agroclimatic domains include irrigated areas where water availability is insufficient to grow lowland rice and/or the cost of irrigation makes it uneconomical to do so, and/or where waterlogging can cause significant yield loss; and rain-fed areas where flooding or soil type and quality cause significant yield losses in non-rice summer crops.

China

There are four main regions in China: I) North Region (comprising the Northeast and Northwest regions); II) North China Plain; III) Southwest Region; and IV) Southeast Region. The Southeast Region is where aerobic rice is currently grown and across which the 69 trial sites under the National Program of Aerobic Rice Regional Trials are located (Figure 2). The spread of these trials across China indicates that aerobic rice is potentially suited to a range of climatic conditions. Estimated aerobic rice areas by province are presented in Table 9. The information contained in this table was obtained by the CAU through field visits, interviews, meetings and official annual reports. The key informants include local government officials, agricultural extension agencies, seed companies and farmers.

Figure 2. National program of aerobic rice: Regional trials in China



Source: Annual Report of NPARRT in China 2009 and Prof. Wang, CAU 2008, pers. comm.

Table 9. Estimated aerobic rice areas and distribution in provinces, China, 2008

Province	Area (ha)
I. North Region [Northeast Sub-Region] (cold, low plain and irrigated)	
Liaoning	35,000
Helongjiang	15,000
Jilin	6,000
Neimenggu	600
I. North Region [Northwest Sub-Region] (cold, dry and irrigated)	
Xinjiang	4,000
Shanxi	3,000
Ningxia	2,000
Gansu	0
Qinghai	0
Xizang	0
II. North China Plain (temperate, low plain and irrigated)	
Henan	20,000
Anhui	20,000
Jiangsu	20,000
Shandong	15,000
Hebei	8,000
Tianjin	2,000
Shanxi	500
Beijing	500
III. Southwest Region (high mountainous and rain-fed)	
Yunnan[1]	100,000
Guizhou	20,000
Guangxi	20,000
Sichuang	8,000
Chongqing	2,000
IV. Southeast Region (subtropical, hilly and rain-fed)	
Zhejiang	8,000
Fujian	7,000
Taiwan	6,000
Jiangxi	6,000
Hunan	5,000
Hubei	5,000
Guangdong	4,000
Hainan	4,000
Shanghai	2,000
Total	**348,600**

Source: Prof. Wang, CAU 2008

Notes: Aerobic rice in Yunnan has been called upland rice (*Lu Dao,* different from *Han Dao*). In Yunnan, most of the improved upland rice (*Lu Dao*) varieties are developed from local traditional varieties which are inbred varieties, with yield relatively lower than hybrid varieties and those aerobic rice varieties growing in Anhui and Henan.

As can be seen from Table 10, the actual area planted to aerobic rice is small relative to the agroclimatic areas where aerobic rice production may have a comparative advantage over either lowland rice or other upland (summer) crops such as maize and soybean.

Table 10. Current aerobic rice area to potentially suitable agroclimate domains

Broad geographic regions	'Suitable' agroclimatic domain	Estimated aerobic rice area	
	ha	ha	%
North China	1,380,000	65,600	4.8
North China Plain	6,660,000	86,000	1.3
South China	3,000,000	197,000	6.6
Total	**10,040,000**	**348,600**	**3.4**

Source: Prof. Wang, CAU 2008

For example, in the North Region, it is estimated that around 30% of the 4.6 million ha of irrigated lowland rice suffers yield losses because of water shortages and yet only 65,600 ha are grown to aerobic rice. In the North China Plain, where an estimated 86,000 ha are used to grow aerobic rice, around 10 million ha of low-lying upland crop areas become waterlogged or saturated from June to September, resulting in 6 million ha of upland grain crops suffering yield losses and an additional 660,000 ha of land either only single-cropped (winter wheat) or lying fallow all year because of flood-induced waterlogging problems. In the rain-fed plateau of the Southwest Region, of the 2 million ha with an annual rainfall higher than 1,000 mm, only an estimated 150,000 ha are sown to aerobic rice.

This is because areas where the rainfall is over 1,000 mm are suited to growing paddy rice. Finally, in the Southeast Region, 3 million ha of lowland rice are threatened by summer or autumn droughts and yet the area sown to aerobic rice is estimated to be around 47,000 ha. Hence, the estimated 348,600 ha currently sown to aerobic rice represent around 3% of the 10.5 million ha that could be potentially used, according to agroclimatic considerations.

Naturally the agroclimatic condition of any location is not the only factor that affects adoption. There are also a number of socioeconomic variables that will affect the uptake of aerobic rice such as the relative profitability of aerobic rice compared with other crops; farmers' desire to produce the family rice requirement rather than purchase rice and to provide a diversified diet; farmers' awareness of and ability to grow aerobic rice and to be able to afford the necessary inputs (fertilizer, pesticides, etc.) to maximize yield or returns; the availability of a range of high-yield varieties that not only suit the local physical environment but also have the taste and cooking qualities demanded by consumers; the availability of seeds; and so forth.

Recognizing this, both biophysical and socioeconomic variables were taken into account to determine the suitability of the aerobic rice technology beyond the research sites as part of the extrapolation domain and scenario analysis undertaken within the STAR project (Rubiano and Soto 2008) (*Objective 5, Output 6*). The potential extrapolation domain (ED) areas for aerobic rice were calculated using Homologue and Weights of Evidence modelling to identify agroecological and socioeconomic conditions that are similar to those found in project pilot sites.

The results of the ED analysis show that the sum of the extrapolation domain areas in China for aerobic rice (at a 60% probability level of finding socioeconomic and climatic conditions similar to those of the pilot sites) is 12.4 million ha, which is similar to the 10.3 million ha estimated by and cited by the CAU. However, when the probability level is increased to 70%, the ED estimate falls to 5.1 million ha. We used the conservative estimate (5.1 million ha) in the analysis.

Even though the results from the ED analysis are preliminary, they provide a starting point in terms of determining adoption levels. Again it would be unreasonable to expect that there would be a 100% adoption rate across the whole ED. A more plausible estimate is based on recent trends in adoption, the improved performance of the newer aerobic rice varieties and commitment to further research on developing drought-tolerant rice varieties, and the increasing water-scarcity problem.

As aerobic rice has been grown in Funan County for 10 years, information from the household surveys undertaken in three villages in Funan County provides an indication of likely adoption trends (Ding *et al.* 2008). In the three surveyed villages, the area sown to aerobic rice was 20% in 2007, an increase of eight percentage points since 2005. The number of farmers growing aerobic rice also increased rapidly from 52% in 2005 to 73% in 2007. At the county level, while the percentage of total land area used for aerobic rice production in Funan was only around 4% in 2007, it still represents a doubling of the adoption rate from 2% in 2005. As stated above, the rapid increase in interest in, and adoption of, aerobic rice was also evident from the key informant interviews (Table 7).

In addition, given the continued research into aerobic rice technologies to address the farmers' needs/concerns (e.g., understanding and addressing yield decline, and the development of more aerobic rice varieties), it seems reasonable to assume that the maximum adoption level could reach 15% of the conservative ED estimate by 2016, which is equal to 765,000 ha.[6] Then if it is assumed that the relative levels of adoption for each of the regions remain unchanged from the 2008 estimates provided in Table 10 (that is 19% for North China, 25% for the North China Plain and 57% for South China), the maximum level of adoption of aerobic rice for North China is 191,945 ha, 251,635 ha for the North China Plain and 576,420 ha for South China (Table 11).

Table 11. Assumed maximum adoption of aerobic rice

Broad geographic regions	**Assumed future level of adoption**
	ha
North China	191,945
North China Plain	251,635
South China	576,420
Total	**1,020,000**

Now that the maximum adoption levels of aerobic rice has been subjectively estimated, the next step is to obtain a plausible estimate of how much of this is due to adoption of CAU varieties. Figure 3 (see p26) shows where CAU varieties have been released. It depicts those areas where the variety was officially released by either state or provincial government authorities. For example, Handao 65 was released by the state government in 2003 and can be disseminated to farmers only in Northeast China; Handao 175 was released by the Guizhou provincial government in 2006 and can be disseminated only in Southwest China; Handao 9 was released by both the State Government of North China in 2003 and by the Guizhou provincial government for dissemination in the Southwest in 2006.

6 The subjective estimate of a 15% adoption level is based on all factors mentioned above. In particular, the growing interest in aerobic rice by researchers, government officials, seed distributors, farmers, etc,; the drivers of change outside the farmers control; the out-migration of farmers to urban areas; and the still to be resolved research issues associated with aerobic rice technologies, such as yield decline and the limited number of varieties currently available to farmers. Moreover, Prof. Wang (2008 pers. comm.) stated that the adoption level would be at least 10% and perhaps as high as 20%, so the midpoint of 15% appears reasonable.

The CAU contribution is estimated to be around 15% of total aerobic rice varieties grown in China in 2008 (Prof. Wang, CAU 2008, pers. comm.).

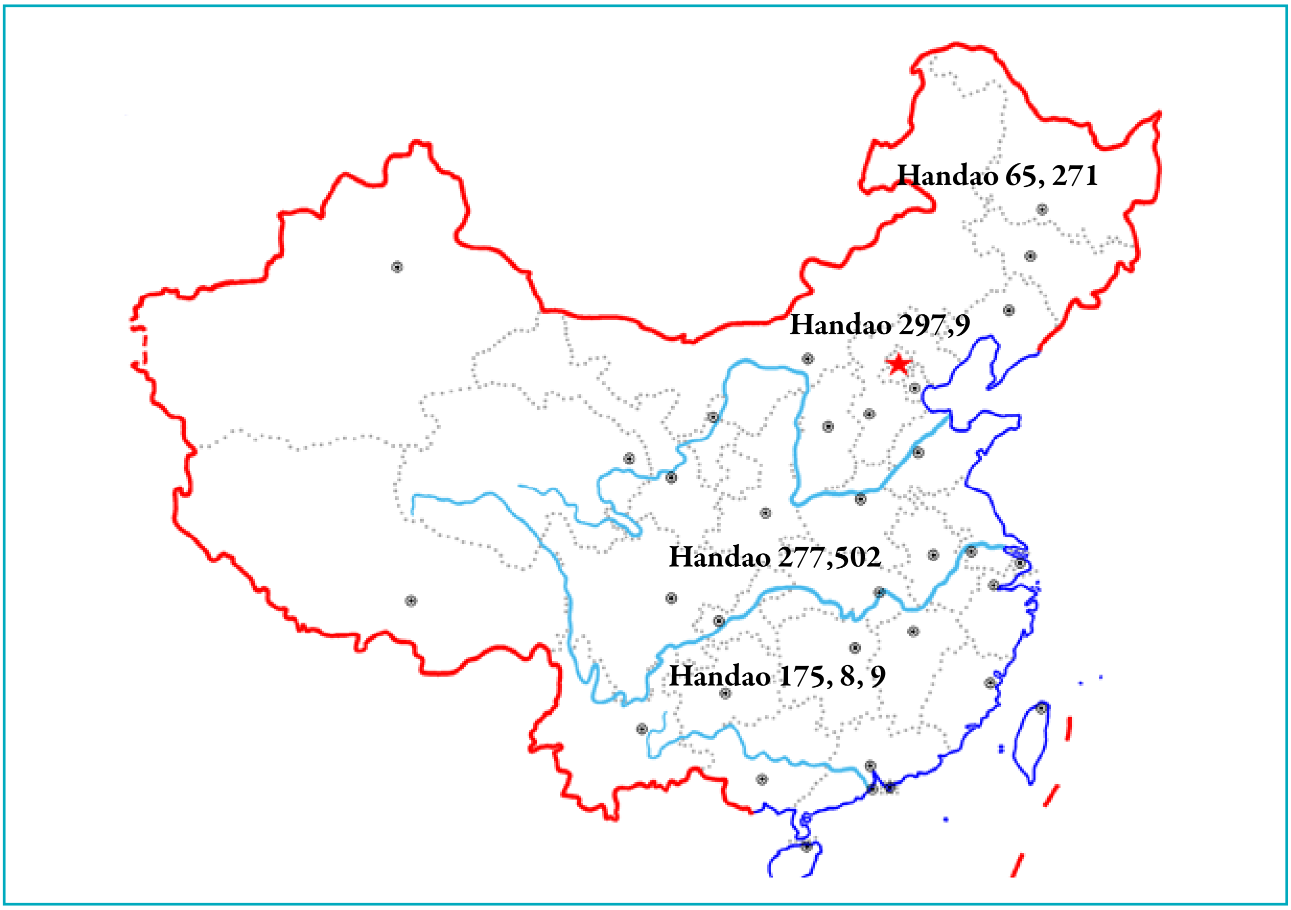
Unfortunately, data are not available at a regional level so the 'national figure' of 15% is used to calculate the total maximum area sown to CAU varieties in China, which is 153,000 ha. According to Prof. Wang, the CAU varieties will be mostly grown in the northern areas of China replacing summer crops (pers. comm. 2009).

In sum, estimating the maximum level of adoption of CAU varieties requires a significant amount of subjective and largely qualitative information. Because of this, a largely conservative approach was used to determine possible future adoption. Hence, the maximum adoption rate should be seen as a lower bound of the potential adoption rate.

The Philippines

In the Philippines, the areas deemed to be potentially suited to aerobic rice technologies were rain-fed where the rain pattern is sufficient for rice production during the wet season (May-November) and irrigated areas where water scarcity is either a physical or economic problem in the dry season (January-May). However, as stated above, (section 4.3), there was little adoption of aerobic rice varieties by early 2008, largely because more trial evaluations are required before aerobic rice technologies can be confidently transferred to farmers. Nevertheless, the ED analysis suggests that around 241,970 ha could be suited to aerobic rice production based on a 70% probability of similarity to the pilot sites (Rubiano and Soto 2008).

Figure 3. Distribution of new varieties of Handao from CAU in farmer areas in China, 2007



Source: Prof. Wang, CAU 2008, pers. comm.

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6. Benefits

6.1 Capacity Impacts

In addition to contributing to the development of technical outputs within the project, human capacity-building can directly benefit both the newly trained individuals and the organization that they work for. The benefit to the individuals is the most direct link between capacity building and impact.

The main benefits to trainees include improvements in confidence, competence, promotion and higher income. Gordon and Chadwick (2007, 30) state that, as a rule of thumb, 'a worker's lifetime income is higher, on average, by around 10% for each additional year spent in formal education.' Hence applying this 'rule-of-thumb' to the 22 students, and nearly 1,600 short-course trainees, the rewards for the trained individual over their working life would be significant.

At the organizational level, the efficiency of CAU was enhanced through the researchers' capacity-induced changes in practice and behavior. This is reflected in increased effectiveness in the provision of technical outputs (identification of the high-yielding potential of a number of aerobic rice varieties – Handao 502, 297, 277 – and the packaging of relatively simple crop management recommendations) and in innovations in the type of services and in the delivery process (farmer participatory research, and farmer demonstrations and training). The recognition of the capacity of CAU to undertake multidisciplinary research on aerobic rice efficiently and effectively enhanced the reputation of the CAU's influence in the policy arena as evidenced by increased international and national funding (subsection 3.3). As a general rule of thumb, workers tend to keep around half of the productivity improvement from training, the other half being captured by the institution (see Gordon and Chadwick 2007).

A similar story is true in the case of the Philippines. Researchers and irrigation managers from national institutes who have been involved in the project activities and/or training on aerobic rice became proactive agents of the technology. One case in point is the initiative of BASC to make their college the Aerobic Rice Center of the Philippines. They received a $25,000 (PhP1,000,000) grant from Japan, through the Philippine National Economic Development Authority, to start the aerobic rice seed production business (Barclay 2008).

The ultimate beneficiaries, apart from the individuals who receive financial and intrinsic benefits from the training, are the final users of the outputs of the research and extension organizations. This is because the community-level impact of investing in capacity-building arises from the technical outputs developed within the project or follow-on research and/or through the improvements at the organizational level that flow from the use of enhanced capacity. In general, while organizational benefits can be largely relative to the investment in training, they are small compared with the returns to the innovations produced if there is significant adoption of these innovations by the final users.

In the case of the STAR project, because the capacity-building activities were an integral and ongoing component of the research, these activities directly contributed to the realization of other output targets within the life of the project, such as the identification of high-yielding aerobic rice varieties and crop/water management techniques. Moreover, given the strength of the capacity built during the STAR project, the skills and knowledge gained by the researchers are likely to be used beyond the STAR project to generate further research deliverables. Areas for further research mentioned by the CAU aerobic rice researchers include varietal improvement (increased diversity and drought and disease resistance, and yield and quality enhancement), improved crop management (in the areas of irrigation and fertilizer application, weed control and yield decline due in monocropped systems) and up-scaling and out-scaling strategies.

Because the capacity built is combined with other inputs to produce the adoptive outputs that ultimately lead to the higher-order outcomes and impacts, the impact at the farm- and community-level is covered in the following section.

6.2 Farm-level Impacts

In general, farm-level impacts for crops stem from a change in yield and/or in the cost of producing those crops. In the case of aerobic rice, there is an added complexity that stems from the fact that aerobic rice may be grown in different locations for fundamentally different reasons. For example, it may be grown in some irrigated areas in response to the increased irrigation costs rather than because water is physically scarce.

In this case, aerobic rice could replace lowland rice varieties as a cost-saving measure even though there is some yield loss. Information from key informant interviews held in Tarlac in the Philippines suggests that farmers, who are currently using pump irrigation to continuously flood their lowland rice crop in the dry season, could save between $330/ha and $395/ha in irrigation costs if they adopt aerobic rice technologies (see Table 12, Appendix 1). Therefore, for as long as the yield sacrifice is less than 1 t/ha, the farmers would be better off. Lower irrigation costs were also cited by farmers in Fentai County (Anhui Province) in China as an important benefit.

Farmers may also replace either lowland rice or other summer crops with aerobic rice in areas where labor is in short supply and hence becoming relatively expensive at critical times in the crop calendar, such as at planting and harvesting. This is particularly true in some poorer areas of China because of labor out-migration. Indeed, as stated above, one of the main benefits of growing aerobic rice cited by farmers in Funan County (Anhui Province) in China (Table 7, Appendix 1), was that it required less labor than either lowland rice or some other summer crops. This concurs with the household survey data presented by Ding *et al.* (2008, Table 6), which found labor costs for aerobic rice are \$28/ha and \$104/ha less than they are for lowland rice and maize, respectively.

Another major reason for choosing to grow aerobic rice in areas where other summer crops, such as maize and soybean, are traditionally grown is to avoid flood-induced crop losses (see Funan County in Table 7, Appendix 1). Similarly, even without the occurrence of waterlogging, farmers may grow aerobic rice as a summer crop rather than grow alternatives because aerobic rice may have a higher profit margin.

The information in the key informant interviews suggests that farmers are substituting aerobic rice for maize and soybean because of its higher profit margin. Conversely, the relative profitability of aerobic rice was not reflected in the results of gross margins analysis undertaken by Ding *et al.* (2008). He reported an average yield of 3.2 t/ha (Ding *et al.*, 2008; Table 9), which is around 3 t/ha below the yield data collected in the key informant interviews undertaken in October 2008 (Table 7, Appendix 1). It should be noted however that the amount 3.2 t/ha was an average over 3 years (2004, 2005 and 2006) across three counties (Fengtai, Yingshang and Funan) and is relatively low because average yield in Yingshang County, where farmers have limited experience in cultivating aerobic rice, is low. However, in the three study villages in Funan County where aerobic rice has been grown for about 10 years, the average yield for the 3 years was 4.86 t/ha, which is more in line with expected yields. Therefore, an assumed yield level of 4.5 t/ha was used as a conservative estimate of farmer yield for aerobic rice in the analysis (Table 13, Appendix 1).

In situations where the yield of aerobic rice is 4.5 t/ha, (a value which is significantly below the yield data obtained from the farmers in the key informant interviews (see Table 7, Appendix 1), and below the yield potential, but being used to for the sake of conservatism), all else being held equal, the gross margin for aerobic rice is 50% below that for lowland rice. This is around \$200-\$400/ha higher than the gross margin for maize and slightly lower than that for soybean when all other price and quantity data are as provided by Ding *et al.* (2008).

Similarly, using the same yield for aerobic rice (4.5 t/ha) and the 2008 cost data for aerobic rice from Ding *et al.* 2008, and applying it to farm-level data for maize and soybean collected by Moya *et al.* (2008), the gross margin for aerobic rice is around \$115 higher than for maize and \$98 higher than for soybean.

7. Benefit-cost assessment

7.1 Capacity Impacts

As presented above, an aim of this study is to determine the economic returns to the STAR investment in aerobic rice technologies. Therefore, to obtain a measure of the returns to the STAR, the benefit attributable to the relevant STAR project is compared with the cost of those projects. However, given the limited information available, the benefit-cost analysis is limited to China, and a number of simplifying assumptions are made:

- The maximum adoption level of aerobic rice in China is assumed to be over 0.7 million ha. This level will be reached by 2016. This appears to be a reasonably conservative estimate given that around 10.5 to 13 million ha is suited to aerobic rice production in China.
- The proportion of aerobic rice varieties attributable to CAU research will remain at the 2008 level, which is 15%.
- In the main, the CAU varieties will be adopted in the northern areas of China and replace summer crops such as maize and soybean.
- Based on gross margin analysis, farmers are at least $100/ha (in 2003 dollars) better-off after substituting aerobic rice for other summer crops such as maize and soybean. Again, this is a conservative measure.

Taking these assumptions into consideration, the total economic benefits are calculated. This is done by multiplying the change in the gross margin by the annual data on the number of hectares sown to CAU aerobic rice varieties and the assumed adoption rate to obtain an annual gross value. The gross value of the annual benefits is then discounted, using a 5% discount rate, to obtain a present value of benefits over a 30-year simulation period. The present value is estimated to be around $136 million (see Table 14, Appendix 1).

7.2 Measure of Benefits Attributable to STAR

Quantifying influence is a difficult task, resulting in a subjective assessment being the common course of action. In the present case, the question of how much of the estimated gains from the development and adoption of CAU aerobic rice technologies are attributable to the STAR project is difficult to address.

However, given the significant contribution the STAR project made to capacity enhancement, the reputation of the CAU aerobic rice program, the role it played in developing an interdisciplinary research program and the increased awareness of the impact pathway, a reasonable conclusion is that the STAR project has made a significant contribution to the returns to CAU aerobic rice varieties. Using the relative importance of the approach to attribution, which apportions the share of benefits on the basis of a subjective assessment of contribution, a plausible, even if conservative, estimate of the contribution made by the STAR project is about 30%. This is a subjective assessment provided by Prof. Wang (2009, pers. comm.). It is based on the knowledge that the

Chinese government has funded 50% of the aerobic rice research undertaken in China and a further 20% is funded through other agencies supporting a number of other (non-STAR) small aerobic rice projects.

Applying the 30% attribution proportion to the present value of CAU aerobic rice varieties, the total benefits attributable to STAR is around $41 million. Given that the research costs for the STAR project are around $1.8 million, even if economic benefits were only ever realized in China, the net present value (NPV) of the STAR project is estimated to be around $39 million over the 30-year time horizon (2003-2032). The corresponding benefit-cost ratio is around 22:1.

Even if farmers are only $50 (in 2003 dollars) better-off after substituting aerobic rice for other summer crops such as maize and soybean, the present value of CAU varieties is estimated to be around $68 million. Therefore, assuming a 30% attribution rate, the NPV of the STAR project is estimated to be around $19 million (over the 30-year time horizon of 2003-2032), and the corresponding benefit-cost ratio is around 11:1. Hence, even under a series of conservative assumptions, the returns to investment are significant.

8. Conclusions, evaluation issues, and areas for further research

Conclusions

Aerobic rice technologies have been developed for production systems that are characterized by physical and/or economic water scarcity, such as those areas visited in China and the Philippines. Aerobic rice is seen as a potentially viable alternative to lowland rice when water scarcity is a limiting factor. Aerobic rice systems are also suited to areas where summer crops are traditionally grown but where both frequent drought and flooding occur such as in the provinces visited in the North China Plain. In these areas farmers are starting to accept that aerobic rice can be grown in the same way as other non-rice summer crops such as maize and soybean.

The main inhibitor to adoption of aerobic rice systems in the past was the inability of some farmers to control weeds. However, with the development, and increased awareness, of post-emergent herbicides, weeds are no longer seen as a major constraint. Low yields were another significant inhibitor to adoption, but the development of new aerobic rice varieties and optimal management techniques has meant that yields of 6 t/ha or higher are now being achieved in farmer fields. The main enablers to adoption of aerobic rice by farmers include reduced labor and water requirements and the fact that aerobic rice is both relatively drought- and flood-tolerant.

The cultivation of aerobic rice is found to be economically feasible and comparable to popular upland crops like maize and soybean. As shown in the analysis, when aerobic rice yields of 4.5 t/ha or more are achieved, the gross margin of aerobic rice is higher than that of maize and soybean. Moreover, in irrigated systems where water is either physically or economically scarce, aerobic rice could be a profitable alternative to lowland rice.

Limiting the returns to China, and applying a 30% attribution figure the present value of the total benefits attributable to STAR is $39 million. Given that the research costs for the STAR project are around $1.8 million, even if economic benefits were only ever realized in China, the NPV of the STAR project is estimated to be $37 million over a 30-year time horizon. The corresponding benefit-cost ratio is 21:1. Hence, even under a series of conservative assumptions, the returns to investment are significant.

Evaluation issues and areas for further research

The primary evaluation issue is the early timing of the assessment and hence the lack of sufficient temporal data for the analysis. In addition, there is a need for clearly defined impact pathways to be developed for each of the target regions. If a follow-up impact assessment work is to be undertaken at least 5 years after the completion of the STAR project, these issues could be addressed.

Further, as stated throughout this Working Paper, the analysis was based on a significant degree of subjectivity and simplifying of assumptions. To more fully deal with the related issues of the correct counterfactual attribution, further information on crop substitution possibilities, and potential yield and input and management changes, for the different domains where aerobic rice may be adopted, as well as a more detailed understanding of the contribution of the STAR project to the spread of aerobic rice are needed. The benefits of capacity-building to individuals could also be quantified empirically in future analyses.

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Appendix 1

Additional information
relating to this Working Paper

Table 1 Summary of project information

Project number	CPWF PN16
Project name	Developing a System of Temperate and Tropical Aerobic Rice (STAR) in Asia
Duration of project	October 2004 to March 2008
Countries	China, India, Lao PDR, Thailand, the Philippines
Funding body	CPWF
Funding amount	US$884,572
Matching fund from participating institutions	US$721,024
Additional source	€163,396 (from GTZ-funded project, *Nutrient management in aerobic rice systems*, implemented from July 2005 to June 2008)
Related CPWF projects	• PN11 – Upper Catchment Rice Landscape Management Basin Focal Project • Extrapolation domain analysis (Rubiano and Soto 2008) • Socioeconomic survey (Ding *et al.* 2008)

Source: IRRI 2004.

Table 2 Country partners by CPWF benchmark basin and share of project activities

CPFW benchmark basins	Project partner country	Project sites	Activities (%)
Yellow River Basin	China	Kaifeng, Henan Province; Changping, Shangzhuang (CAU) and Xibeiwang villages near Beijing; and in Fengtai and Mencheng counties, Anhui Province	45
Non-CPWF Basin Areas	The Philippines	San Ildefonso in Bulacan, Dapdap and Muñoz in Tarlac, and Nueva Ecija	30
Indo-Gangetic Basin	India	Bulandshahar District, western Uttar Pradesh, WTC-IARI Station, New Delhi	20
Mekong River Basin	Lao PDR	Vientiane, Savannakhet and Champasak	5
	Thailand	Khon Kaen, Ubon Ratchathani and Phimai	

Source: IRRI 2004.

Table 3 Participating institutes and project team members

Country	Participating institute	Project team
Partners with funding from CPWF		
China	CAU	Wang Huaqi, Yang Xiaoguang, Lin Shan, Xie Guanghui, Liping Feng, Tao Hongbin, Zhang Limeng, Xue Changying, Yan Jing, Yu Jun, Xiao Qindai
The Philippines	IRRI	B.A.M. Bouman (Project Leader), G. Atlin, Dule Zhao, Shaobing Peng, C. Kreye, R. Lampayan, P. Moya, R. Bayot, R. Flor, L. Llorca, E. Quicho
The Philippines	National Irrigation Administration Tarlac (NIA-Tarlac)	V. Vicmudo, A. Lactaoen, T. Norte
The Philippines	Philippine Rice Research Institute (PhilRice)	J. de Dios, A. Espiritu
India	Indian Agricultural Research Institute - Water Technology Centre (IARI-W)	Anil Kumar Singh, Viswanathan Chinnusamy, S.K. Dubey
Thailand	Ubon Ratchathani Rice Research Centre (URRCR)	B. Jongdee, P. Konghakote (Khon Kaen Rice Research Centre)
Lao PDR	National Agricultural and Forestry Research Institute (NAFRI)	Kouang Douangsila, Nivong Sipaseuth
Germany	Institute of Plant Nutrition and Soil Science (IPNSS) Christian-Albrechts-Universität zu Kiel	K. Dittert
Partners without funding from CPWF		
The Philippines	Central Luzon State University (CLSU)	A. Espino
The Philippines	Bulacan Agricultural State College (BASC)	J. Valdez, J. Soriano
The Philippines	National Soil and Water Resources Research and Development Center – Bureau of Soil and Water Management (BSWM)	B.V. Villanueva

Source: IRRI 2008b.

Table 4 Funding provided by cash and in-kind (US$)

	2005	2006	2007	Total
Contributed funds				
CPWF	320,508	315,720	248,344	**884,572**
Matching funds (cash or in-kind)				
IRRI	165,624	140,503	88,146	**394,273**
CAU-Beijing	34,500	34,890	35,288	**104,678**
NIA	13,550	13,746	13,946	**41,242**
PhilRice	16,055	16,306	16,562	**48,923**
IARI-WTC	18,750	19,002	19,259	**57,011**
NAFRI	0	0	0	**0**
URRRC	0	0	0	**0**
CAU-KIEL	24,532	24,963	25,402	**74,897**
Total Matching	273,011	249,410	198,603	**721,024**
Total	**593,519**	**565,130**	**446,947**	**1,605,596**

Source: IRRI 2004.

Table 5 Achievement of intended outputs

Intended outputs	**Achievement status by country**	
	China	
1. First generation of tropical aerobic rice germplasm with high yield potential, and improved aerobic rice varieties in China	Achieved: Identified the yield potential and suitability of three main aerobic rice varieties HD277, HD297, HD502	»
2. Basic crop-water and crop-nutrient relations understood	Partly achieved: Further research on nitrogen and micronutrients needed	»
3. Prototype aerobic rice production systems focusing on water and nutrient management, crop establishment, weed control, and crop rotations	Largely achieved: Research on irrigation and agronomic management (e.g., row spacing and seed rate) undertaken in-country and general information on other crop-management options provided; no research to date/long-term trials on sustainability	»
4. Key sustainability and environmental impact indicators identified	Not planned: In-country research activities were not undertaken	»
5. Trade-offs between water use and yield quantified, and impact on water savings assessed	Largely achieved: Field and modeling studies undertaken. Further research needed to quantify actual water savings at field and spatial-system scales and "downstream" impacts	»
6. Potential target domains characterized in biophysical and socioeconomic terms	Largely achieved	»

Achievement status by country				
	The Philippines	India	Lao PDR	Thailand
»	Achieved: Identified suitable and released varieties Apo (PSBRc9), UPLR15, PSBRc80	Achieved: Identified suitable and released varieties loke Pusa Rice Hybrid 10, Proagro6111 (hybrid), and Pusa834	Not achieved: Progress was made in identifying higher yielding germplasm; further research needed to develop suitable varieties	Not achieved: Progress was made in identifying higher yielding germplasm; further research needed to develop suitable varieties
»	Partly achieved: Further research on the relationship between soil sickness for aerobic rice and the nitrogen source and management needed	Partially achieved: Further research needed to determine if yield can be increased by changing fertilizer management	Not planned: Limited number of experiments on crop-nutrient response conducted	Not planned and not achieved
»	Largely achieved: Row-spacing experiments were undertaken in-country and general information on other crop-management options provided	Partly achieved: Seed rate experiments were undertaken in-country and general information on other crop-management options provided	Not planned and not achieved	Not planned and not achieved
»	Partially achieved: Further research needed	Not planned and not achieved	Not planned and not achieved	Not planned and not achieved
»	Partially achieved: Further research needed to quantify actual water savings at field and spatial-system scales and "downstream" impacts	Partially achieved: Further research needed to quantify actual water savings at field and spatial-systems scales and "downstream" impacts	Not planned and not achieved	Not planned and not achieved
»	Not achieved	Not achieved	Not achieved	Not achieved

Table 6 Key informants

Date	Place	Key informant(s)
The Philippines: Tarlac and Bulacan Provinces		
5 March 2008	National Irrigation Administration Office, Tarlac City, Tarlac, the Philippines	Dr. Vicente Vicmudo (Manager), and Mr. Armilito Lactaoen (Researcher)
5 March 2008	Barangay Canarem, Victoria, Tarlac, the Philippines	Mr. Ramon Ganiban (Farmer), and Mr. Manuel Apolonio (Farmer)
6 March 2008	Bulacan Agricultural State College, San Ildefonso, Bulacan, the Philippines	Dr. Junel Soriano (Director for Research, Extension and Training)
6 March 2008	Norzagaray, Bulacan, the Philippines (Field day)	Farmers from Barangay Bangkal, Barangay Banaca, Barangay Matiktik, Barangay Partida, and Barangay Tigbi in Norzagaray, Bulacan. Representatives from Bulacan Provincial Agricultural Office, Municipal Office of Norzagaray, the National Economic and Development Authority, and Bulacan Agricultural State College
6 March 2008	San Ildefonso, Bulacan, the Philippines	Mr. Nemencio Concepcion (Farmer)
China: Anhui and Henan Provinces, and Beijing		
13 October 2008	China Agricultural University (CAU), Beijing, China	Prof. Wang Huaqi, Dr. Yang Xiaoguang, Dr. Lin Shan, Dr. Xie Guanghui, Dr. Tao Hongbin (CAU staff who are involved in the project)
15 October 2008	Fengtai County, Anhui Province, China	Mr. Liu Shichong (County Official)
15 October 2008	Shangtang town, Fengtai County, Anhui Province, China	Mr. Li Guomin (Town Official) Mr. Wang Chenguo (Farmer)
16 October 2008	Market place, Shangtang town, Fengtai County, Anhui Province, China	Cheng Longfei, An Fenli, Li Zhifu, Wang Li, Sun Fangli (Farmers)
16 October 2008	Shangtang town, Fengtai County, Anhui Province, China	Two aerobic rice farmers and two lowland rice farmers Mr. Hu Qilin (Agricultural Supply Shop Owner)
17 October 2008	Funan County, Anhui Province, China	Mr. Xiang Tianfu (County Official) and Mr. Ding Guangli (Funan Agricultural Science Research Institute) Mr. Hou and Mr. Zhao Wei (Seed distributors)
17 October 2008	Heshong village, Funan County, Anhui Province, China	Four aerobic rice farmers
17 October 2008	Collective farm producing seeds, Funan County, Anhui Province, China	Three farmers

Date	Place	Key informant(s)
17 October 2008	Fupo village, Funan County, Anhui Province, China	Three aerobic rice farmers
18 October 2008	Dingzhai village, Funan County, Anhui Province, China	Five farmers
18 October 2008	Rice mill, Funan County, Anhui Province, China	Mr. Xiang (Town official), and Mr. Lei (ATES staff)
18 October 2008	Collective farm producing lowland rice (direct-seeded), Funan County, Anhui Province, China	Mr. Zhang (providing technical support to farmers)
19 October 2008	Xincai County, Henan Province, China	Mr. Gao Junshan (Manager of a seed company) Mr. Ren (ATES staff)
20 October 2008	Xincai County, Henan Province, China	Mr. Ma (Xincai Bureau of Agriculture)
20 October 2008	Fuyang City, Anhui Province, China	Mr. Ren Yiming (Manager of a seed company)
22 October 2008	The CAU, Beijing, China	Prof. Wang Huaqi, Dr. Yang Xiaoguang, Dr. Lin Shan, Dr. Feng Liping, Dr. Dingming Kang (CAU staff who are involved in the project)

Table 7 Information from informant interviews: Anhui and Henan provinces, China, October 2008: Area, yield, variety and factors affecting adoption.

No.	Location	Informant	Lowland rice area (ha)	Lowland rice yield (t/ha)	Aerobic rice area (ha)	Aerobic rice yield (t/ha)	Aerobic rice varieties	
Anhui Province, Fentai County								
1	Fengtai	County official	570,000	7.5 - 7.9	10,000	3.7 - 6.0		»
2	Shangtang township	Town official	23,000	7.8	2,300	5.0		»
3	Shangtang township	Farmer – President of (natural) village			0.05	5.2		»
4	Shangtang township market	Group of farmers randomly selected at the market place (two lowland rice; three aerobic rice)		6.0 - 8.2		4.5 - 7.5	HD502	»
5	Cuihai village	Group of farmers (two lowland rice; two aerobic rice)		6.0		5.2	HD502, 277	»
6	Shangtang township	The manager of agribusiness	1,530		200		HD502, 277	»

	Problems with or reasons for not growing aerobic rice	Benefits of growing aerobic rice	Dissemination of aerobic rice
»	Enough water to grow lowland rice, which is higher-yielding than aerobic rice; drought and flooding also not common	Change in government subsidies for grain crops has led to a reduction in nongrain crops. Cost of pumping has increased significantly	Farmers obtain some crop information from Agricultural Technology Extension Station (ATES). However, most farmers obtain information on aerobic rice from seed company / distributors / agribusinesses and from the fact sheets, posters, and brochures these businesses produce
»	Weed problem; no subsidy for aerobic rice	Requires less water than lowland rice, stable yield, fewer pesticides, less labor, lower irrigation costs	Not stated
»	No subsidy for aerobic rice; weed and insect problems	Grows aerobic rice in low-lying areas because of higher returns than soybean and not enough water for lowland rice	Agribusiness (primarily Mr. Hu) provides information on varieties and appropriate management strategies
»	Not suitable for upland area, water scarcity not a problem	Labor and water shortage, irrigation costs are too high; stable yield	Agribusiness (primarily Mr Hu) provides information on varieties and appropriate management strategies
»	Water scarcity not a problem for lowland rice; grows maize because of high altitude	Water became scarce but land is still flood-prone; labor-saving; stable yield	Agribusiness (primarily Mr. Hu) provides information on varieties and appropriate management strategies
»			The manager of the agribusiness is the main source of information to the farmers in nearby villages. He and his family own several shops selling agricultural inputs. Around 60 farming households obtain aerobic rice seed from Mr. Hu. Altogether, around 90 farming households grow aerobic rice

No.	Location	Informant	Lowland rice area (ha)	Lowland rice yield (t/ha)	Aerobic rice area (ha)	Aerobic rice yield (t/ha)	Aerobic rice varieties	
Anhui Province, Funan County								
7	Funan	Manager of seed company/ agribusiness	Dry season lowland rice is grown on 30% of the total rice area Zhongyou Zhao 5	7.9	35% of total rice area is aerobic rice = honghai209, 201; 35% of total rice area is aerobic rice = Lvhan1	6.0 – 6.5	HD 502 (2000-02); Lvhan1 (2005); Longhan209, 221 (2006)	»
8	Funan	Seed distributor/ agribusiness	20% irrigated lowland rice	8.4	50%	6.5	Lvhan1	
					10%	6.75	Zhonghan209	
					10%	5.5 – 6.5	HD502	
					10%	5.5	Xinhan1	»
9	Funan	Director of ASTI					The local research station (under the Bureau of Agriculture) tests varieties for local adaptability The most promising varieties: Lvhan1, Zhonghan 209, 502	»
10	Hesheng village - Xiau Dai Natural village	Farmers			80% of farmers	6.0	HD277	
						6.7	HD502	»
						8.2	906	
11	Fumeng State Farm	Leader of collective farm; 73 ha and 110 farmers	60% soybean		20%	7.2	Lvhan1	
					12%	6.3	Zhonghan209	
					8%	ns	Other	»

	Problems with or reasons for not growing aerobic rice	Benefits of growing aerobic rice	Dissemination of aerobic rice
»	Dry-season lowland rice variety is of shorter duration; weeds are a problem so farmers need to use herbicides.	Flood-prone area; good yield; low labor and irrigation costs compared with paddy.	Government-advertised variety; magazine; asks friend to bring new varieties for the seed distributor to test. Provides farmers with information on aerobic rice varieties and optimal management strategies such as weed control and irrigation rate (three times in dry year).
»	Direct-seeded lowland rice varieties in aerobic soil are common in the county.	Less labor; lower production cost; good profit due to high and stable yield. The mention of stable yield here is in contrast to the findings of the 2007 survey (Ding *et al*. 2008).	He receives information on aerobic rice varieties from seed dealers, Agricultural Technology Extension Station (ATES), the Internet and magazines. Provides farmers with information on aerobic rice varieties and optimal management strategies (seed density = 4 kg/mu; irrigation = 2-3 times in a drought year; weed control = use herbicide.
»		Benefits include good yield, simple management - less labor, less water. Overall, aerobic rice has a bright future as it is well suited to the local environment.	Long history of aerobic rice production (including direct-seeded lowland rice varieties in the aerobic soil) in the county Varieties from other sources - e.g., CAU Prof. Wang held training courses in 1994. The ATES now collaborates with CAU. The MoA established national variety experiment plots for aerobic rice and other non-aerobic rice varieties. Aerobic rice is now part of the regular training/ demonstration activities. The main focus of the training, which targets agricultural technicians and farmers, is to introduce new varieties and management techniques.
»	Weed problem.	Labor and water saving.	One farmer had participated in a varietal selection activity organized by Prof. Wang in 1996.
»	Soybean has lower economic margin than aerobic rice, but also requires less labor and water and can be grown in lower-quality soil.	Higher returns than other summer crops. Increased demand for seeds has led to doubling of the area grown to aerobic rice - from 13 ha to 27 ha.	The Fumeng State Farm provides farmers with aerobic rice seeds.

No.	Location	Informant	Lowland rice area (ha)	Lowland rice yield (t/ha)	Aerobic rice area (ha)	Aerobic rice yield (t/ha)	Aerobic rice varieties	
12	Fupo village	Three farmers plus head of commune				6.7	Lvhan1 - Better disease tolerance, maturity, color and drought tolerance	»
						6.7	HD502- Better taste	
13	Dingzhai Natural Village	Five farmers			95%	7.9 6.0 - 6.5	Zhonghan 209, Zhongyou Zao 5, which is a lowland rice variety, is also direct seeded grown aerobically) HD502, 277	»
14	Dingzhai Natural village	Local miller	70%		30%			»
15	Funan	Large farm	800	7.5	53	5.4 – 6.0	HD502 Lvhan1 Jinggoa1 some from other province	»

	Problems with or reasons for not growing aerobic rice	Benefits of growing aerobic rice	Dissemination of aerobic rice
»		All three farmers grow aerobic rice because higher yield/better returns than other summer crops. It also uses less labor, water and pesticides than lowland rice	Originally it was seed distributors who disseminated aerobic rice technologies. They are still the main source of information However, in 1996, the Bureau of Science and Technology held training workshops and the town technicians passed their knowledge and skills to the village technicians who, in turn, taught the farmers. The training workshops and demonstrations are held for all crops, not just for aerobic rice.
»	Weed problem - need herbicide; more complicated than growing paddy; not enough varieties to choose from.	The farmers do not grow other summer crops because of soil quality and waterlogging. They like aerobic rice because it requires less labor, less water and the yield is high and stable. They receive government support.	Prof. Wang told them about aerobic rice originally and provided training. They obtain information on new varieties and crop management from ATES and local technicians.
»	Aerobic Rice produces more broken grains, according to the local miller. Broken grains have lower market value compared to head rice. 'Brokens' are higher in aerobic rice.		
»	Aerobic rice has a long history in the area but weeds were a big problem so farmers stopped growing this rice. Last year farmers started to grow again because of new varieties and availability of post-emergence herbicide.	Prefer to grow aerobic rice or dry-season lowland rice to soybean or maize which has a lower yield because of waterlogging problems. Profit 20-40% more than other summer crops.	The farm manager was aware of aerobic rice technologies through his earlier association with Prof. Wang (CAU). Farmers come to him for advice on aerobic rice - varieties and management. In this county aerobic rice accounts for 25% of the summer crops. In the surrounding 10 km, the use of aerobic rice seed production will increase because of the increased demand.

No.	Location	Informant	Lowland rice area (ha)	Lowland rice yield (t/ha)	Aerobic rice area (ha)	Aerobic rice yield (t/ha)	Aerobic rice varieties
Henan Province, Xincai County							
16	Zaolin Natural village	Four farmers				6.7	Zhenghan2
						7.0	Xinhan1
17	Gaowan Natural village	Five farmers			61%	6.7	Zhenan2
18		Breeder/seed company					
19		Director of Xincai Agricultural Extension Service				6.5	Zhenghan 1,2,3 Xinhan1,2 Handao502 Chaoyou1
20		Deputy Director Xincai Bureau of Agriculture	2,000		8,000	6.0 – 7.5	
21	Fuyan	Manager of seed company			There will be 13 ha of aerobic rice seed production in 2009	6.0	Farmers prefer Indica varieties

Note: The high yields for aerobic rice are largely due to the exceptionally good season in terms of the timing and quantity of rainfall.
Source: Information obtained from key informant interviews: October 2008.

	Problems with or reasons for not growing aerobic rice	Benefits of growing aerobic rice	Dissemination of aerobic rice
»	Not enough aerobic rice seed available.	Yield higher than other crops and better profit.	Seed Company.
»	Weeds were a problem but now good herbicides are available so restarted to grow in 2003.	Waterlogging not a problem; yield is higher than other summer crops; requires less labor; good eating quality.	Seed Company (Mr. Gao). It is his family village.
»	The company was Xincai Rice Research Association from 1993 to 2007 when it was privatized. At that time the current Manager of the seed company (Mr. Gao Junshan) retired from the Bureau of Agriculture as a Senior Agronomist. The company provides aerobic rice seeds to the local farmers. Xincai County suffers from waterlogging. In view of this problem, the government extension workers recommended aerobic rice as a summer crop. Aerobic rice was introduced to farmers through the media – primarily the Henan Daily. In 1991, several aerobic rice demonstration plots were established in Xincai County. The interest in aerobic rice has increased over time. This is because the yield is higher than it is for other summer crops. It also requires less labor and has a good eating quality. As such, Mr Gao believes the interest in aerobic rice will continue to grow – from around 60% of farmers interested in growing aerobic rice now to 90% by 2020. Mr. Gao developed Xinhan1 and Xinhan3.		
»	The Director believes that aerobic rice has a bright future as the development and promotion of aerobic rice are well seated in the National Grain Industry Development Policy for food Security. Aerobic rice suits the local environment because 29,000 ha (out of a total agricultural area of 98,667 ha) are flood-prone. In addition, over the past 59 years there have been 19 droughts. About 70% of summer crop production losses is due to waterlogging and 20-30% of lowland rice losses is due to drought. As a result of the severe waterlogging problem, and intermittent droughts, the local government is promoting aerobic rice. Over time, the yield of aerobic rice has increased from 3 t/ha to 6.8 t/ha because of the development of improved varieties, more effective use of herbicides and pesticides and because of the government support – training subsides and agricultural infrastructures.		
»		Simple management, and no irrigation necessary in a normal year. Significant increase in aerobic rice over the past 3 years replacing soybean, cotton, maize, and sesame. Maize area has also increased and is the main summer crop (40,000 ha). Cotton is labor-intensive and soybean has a lower profit.	Dissemination of aerobic rice is undertaken primarily by private seed companies - not the Bureau. The Bureau trains staff and can support technicians. Demonstration and training activities are supported by ATES. The Deputy Director believes aerobic rice has a bright future.
»	Farmers do not like Handao277, 297, 502		Mr. Ren has close association with Prof. Wang. Coop invites farmers for demonstrations.

Table 12 Fuel costs under full irrigation and controlled irrigation, dry season, Tarlac, 2007

	Full irrigation	**Controlled irrigation**
Fuel consumption to pump water (L/hr)	4	4
Hours of pumping per ha per application	10 - 12	5 - 6
Applications per season	16	12
Total hours of applications per seasons	160 - 192	60 - 72
Total (amount of fuel used per season per hectare)	640 - 768	240 - 288
Price of fuel per liter	40	40
Total pumping costs per season (PhP)	25,600 - 30,720	9,500 - 11,520
Cost savings (PhP)		16,000 - 19,200
Cost savings ($)		330 - 395

Source: Key informant interviews, Tarlac, the Philippines, 2008.

Table 13 Comparisons of gross margins of aerobic rice and maize in Fengtai and Funan provinces

	Fengtai			**Funan**		
	Aerobic rice	**Lowland rice**	**Maize**	**Aerobic rice**	**Lowland rice**	**Maize**
Revenue						
Yield (t/ha)	4.50[(a)]	7.15	3.92	4.50[(a)]	6.29	2.99
Price ($/ha)	257.83	246.29	170.66	189.30	172.34	173.24
Production value ($/ha)	1160.22	1761.00	669.00	851.85	1084.00	518.00
Cost						
Seed ($/ha)	90.9	68.6	56.3	67.8	80.4	65
Pesticide ($/ha)	90.6	106.8	47.2	97.7	125.4	43.2
Fertilizer ($/ha)	190.9	225.1	165.9	198	230.2	174
Fuel and oil ($/ha)	55.8	37.9	37.2	50	55.1	27.4
Rent ($/ha)	85.5	177.3	9.9	122.1	141.7	40.8
Labor cost ($/ha)	205.5	255.7	320.8	240.8	303.2	307
Total cost	**719.2**	**871.4**	**637.3**	**776.4**	**936**	**657.4**
Gross margin ($/ha)	441.02	889.60	31.70	75.45	148.00	-139.40

[a] Used as an illustrative, even if conservative, example. *Source*: Ding *et al.* 2008, Table 6.

Table 14 Present value of benefits from growing CAU aerobic rice varieties, 2003 - base years

Year	Total potential sown to aerobic rice ha	Adoption rate	Area adopted ha	Area sown to CAU varieties ha	Farmer benefits ($/ha)	Total benefits ($)	Discount rate (5%)	Present value of benefit ($)
2003	5,100,000	0.06	300,000	45,000	100	4,500,000	1.00	4,500,000
2004	5,100,000	0.06	320,000	48,000	100	4,800,000	0.95	4,571,429
2005	5,100,000	0.07	333,000	49,950	100	4,995,000	0.91	4,530,612
2006	5,100,000	0.07	340,000	51,000	100	5,100,000	0.86	4,405,572
2007	5,100,000	0.07	345,000	51,750	100	5,175,000	0.82	4,257,485
2008	5,100,000	0.07	348,600	52,290	100	5,229,000	0.78	4,097,058
2009	5,100,000	0.08	408,000	61,200	100	6,120,000	0.75	4,566,838
2010	5,100,000	0.10	510,000	76,500	100	6,885,000	0.71	4,893,041
2011	5,100,000	0.12	612,000	91,800	100	7,650,000	0.68	5,177,821
2012	5,100,000	0.14	714,000	107,100	100	8,415,000	0.64	5,424,384
2013	5,100,000	0.16	816,000	122,400	100	9,180,000	0.61	5,635,724
2014	5,100,000	0.18	918,000	137,700	100	9,945,000	0.58	5,814,636
2015	5,100,000	0.20	1,020,000	153,000	100	10,710,000	0.56	5,963,729
2016	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.53	6,085,437
2017	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.51	5,795,655
2018	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.48	5,519,671
2019	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.46	5,256,830
2020	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.44	5,006,504
2021	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.42	4,768,100
2022	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.40	4,541,047
2023	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.38	4,324,807
2024	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.36	4,118,864
2025	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.34	3,922,727
2026	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.33	3,735,931
2027	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.31	3,558,029
2028	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.30	3,388,599
2029	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.28	3,227,237
2030	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.27	3,073,559
2031	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.26	2,927,199
2032	5,100,000	0.20	1,020,000	153,000	100	11,475,000	0.24	2,787,809
Total								**135,876,335**

Appendix 2

Key 'STAR Project' Publications

B.A.M. Bouman, Feng Liping, To Phuc Tuong, Lu Guoan, Wang Huaqi, Feng Yuehua. 2007. Exploring options to grow using less water in northern China using a modelling approach. II. Quantifying yield, water balance components, and water productivity. *Agricultural Water Management* 88: 23-33.
DOI 10.1016/j.agwat.2006.10.005

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 Liuyuankou Irrigation System, Henan, where surface water and groundwater are conjunctively used. 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 rain-fed cultivation, while maintaining yields at 6,400-9,200 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 rain-fed cultivation. In the transition zone between lowland rice and upland crops, the depth of groundwater tables varies from 10 cm to more than 200 cm, and aerobic rice yields vary from 3,800 to 5,600 kg ha^{-1}, which are feasible with as little as 2-3 supplementary irrigations (totalling 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.

C. Kreye, B.A.M. Bouman, A.R. Castañeda, R.M. Lampayan, J.E. Faronilo, A.T. Lactaoen, L. Fernandez. 2009. Possible causes of yield failure in tropical aerobic rice. *Field Crops Research* 111: 197-206
DOI 10.1016/j.fcr.2008.12.007

Abstract
Aerobic rice is a water-saving rice production system for water-short environments with favorable soils and adapted, potentially high-yielding varieties that are direct dry seeded. Soils remain aerobic but supplementary irrigation is applied as necessary. In the dry seasons of 2004 and 2005, an experiment on water by an N experiment (nitrogen [fertilizer] as the treatment) was set up at the location "Dapdap" in Central Luzon, Philippines, to explore water and N management strategies in aerobic rice. The experiment was laid out as a split-plot design on a loamy sandy soil with three water treatments (irrigation twice per week, once per week, and once in two weeks with modifications) and 5 N levels (0 - 200 ka ha^{-1}). Average seasonal soil moisture tension ranged from 9.2 to 20 kPa but yield hardly responded to the treatment combinations and ranged from 0 to 2 tha^{-1}. In addition to trial-specific parameters, root knot nematodes and micronutrients (2005) were monitored. Galling of roots due to nematodes was assessed through a rating scale of 0-5, with 0 = no galling and 5 = >75% of the root system galled. The degree of galling reached a level of 5 at flowering and harvest in 2004, and 3 at tillering and 4 at harvest in 2005. Results of a plant tissue analysis at mid-tillering for Fe, Mn, and Zn showed, on average, values above critical levels; individual replicates, however, indicated deficiencies for Mn. In addition to actual field observations, we used simulation modelling (ORYZA2000) as a tool to estimate attainable yield under actual water conditions and N inputs to explore how yield failure set in. Simulation results matched observed values for total above-ground biomass and leaf area index quite well when no N was applied. When high rates of N (200 and 165 kg ha^{-1}) were applied, simulated values matched actual field data only until about the panicle initiation stage; afterwards, observed values remained below the simulation value. We interpreted this as evidence that growth-limiting factors other than water or N affected the crop from this growth stage onwards. Observations made in the field on root knot nematodes and micronutrients suggested that these two factors, especially root knot nematodes, may have been major constraints to crop development in this experiment.

C. Kreye, B.A.M. Bouman, G. Reversat, L. Fernandez, C. Vera Cruz, F. Elazegui. 2009. Biotic and abiotic causes of yield failure in tropical aerobic rice. *Field Crops Research* 112: 97-106.
DOI 10.1016/j.fcr.2009.02.005

Abstract
Aerobic rice is a new production system for water-short environments. Adapted varieties are usually direct dry seeded and the crop grown under aerobic soil conditions with supplementary irrigation as necessary. Occasionally, yield failures occur which may be related to soil health problems. In the dry seasons of 2006 and 2007, we conducted a field experiment in the Philippines, to identify the major causes of such yield failure. Four treatments were implemented: a) control of direct dry-seeded rice (improved upland variety Apo); b) Biocide application; c) transplanting into aerobic soil; and d) 1 year fallow. Yield in the Biocide treatment was 2 tha^{-1} in both years. In all other treatments, yield was 0 - 0.3 t ha^{-1}. Plants grown in the Biocide treatment showed a reduced degree of galling of roots caused by root-knot nematodes (RKN) and better general root health than in the control treatment. Potentially pathogenic fungi were isolated from root samples (Pythiumsp., Fusariumsp., and a Rhizoctonia-like species). Abiotic effects of the Biocide treatment were an increase in KCl-extractable N (initial season, 2007) and a decrease in initial soil pH. In the control treatment, soil pH increased from 6.5 to 8.0 over the two seasons. In 2007, plant tissue analysis indicated Mn deficiency in the control treatment. Plants subjected to foliar micronutrient sprays reacted positively to Fe and Mn sprays in the control treatment, and Mn spray in the Biocide treatment. We concluded that the Biocide application led to favorable soil conditions by reducing biotic stresses such as RKN and improving nutrient availability. In the other treatments, an interaction of RKN and micronutrient deficiencies with increasing soil pH led to yield failure.

Feng Liping, B.A.M. Bouman, To Phuc Tuong, R.J. Cabangon, Li Yalong , Lu Guoan, Feng Yuehua. 2007. Exploring options to grow rice using less water in northern China using a modelling approach. I. Field experiments and model evaluation. *Agricultural Water Management* 88: 1-13.
DOI 10.1016/j.agwat.2006.10.006

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 non-flooded 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 4 years of field experiments on AWD and aerobic rice in 2001-04 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 8,000 kg ha^{-1} with 900 mm of 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 2,400 - 3,600 kgha^{-1}, using 750 - 1,100 mm of 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. 2010. Yield of aerobic rice in rain-fed lowlands of the Philippines as affected by N fertilization and row spacing. *Field Crops Research* 116: 165-174.
DOI 10.1016/j.fcr.2009.12.007

Abstract
This study evaluated the effects of different N amounts and timing of N applications and row spacings on yields of aerobic rice under rain-fed 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 the 2005 wet seasons, and b) N-split application by row spacing (NS x RS) in PhilRice during the 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 main plot and row spacing as subplot. In the NA x RS experiment, five N levels were used: 0, 60, 90, 120 and 150 kgha^{-1}. For NS x RS, a total fixed rate of 100 kgha^{-1} were applied, but under five different timing of application in percent: 0-30-30-30-10 (NS1), 0-20-50-30-0 (NS2), 0-20-30-50-0 (NS3), 23-23-29-25-0 (NS4), and 18-0-29-43-10 (NS5) 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 (RS25), 30 cm (RS30), and 35 cm (RS35). Results showed that under rain-fed condition, about 3.1 to 4.9 tha^{-1} of grain yields of aerobic rice can be obtained with the addition of 60-150 kg Nha^{-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 that this is also applicable for aerobic rice under rain-fed conditions. 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 spikelets per panicle in the wider spacing. The percent of filled spikelet was also slightly higher in the wider spacing than in the narrow spacing. We did find a 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. 2009. Response of yield determinants and dry matter translocation of aerobic rice to N application on two soil types. *Field Crops Research* 114: 45-53.
DOI 10.1016/j.fcr.2009.07.001

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, called 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 kgNha^{-1} (N0), 75 kgNha^{-1} (N1) and 150 kgNha^{-1} (N2), split applied at the 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 tha^{-1} as influenced by N fertilizer rates and site conditions. At Shangzhuang site in 2005, HD297 combined a high above-ground biomass (15.6 t dry matter ha^{-1}) with a low harvest index (averaged 0.30) at the seeding rate 135 kgha^{-1}. 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. Translocation of dry matter from vegetative organs into grains increased with N fertilizer rates, but the mean of translocated dry matter was relatively low, with only 1.08 tDMha^{-1}. The efficiency of translocation of dry matter ranged from 3.7 to 34.9%. And the contribution of pre-anthesis assimilates

to grain was 10.9-65.7% which differed with N supply. Translocation of low dry matter was 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 production of dry matter and greater spikeltets per m^2 at Shangzhuang site contributed to the higher grain yield compared to that in the CAU site.

Lixiao Nie, Shaobing Peng, B. 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. The solophos rate was 4,407.5 kg ha^{-1} 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, B. 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.
DOI 10.1007/s11104-007-9402-6

Abstract
"Aerobic rice" system is the cultivation of nutrient-responsive cultivars in non-flooded 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 non-flooded 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 the 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 caused by continuous cropping of aerobic rice.

Lixiao Nie, Shaobing Peng, B. A.M. Bouman, Jianliang Huang, Kehui Cui, Romeo M. Visperas, and Jing Xiang. 2008. Alleviating soil sickness caused by aerobic monocropping: Responses of aerobic rice to nutrient supply. *Field Crops Research* 107: 129-136.
DOI 10.1016/j.fcr.2008.01.006

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. A micro-plot experiment was conducted in the 2005 dry season (DS) in a field where aerobic rice has been grown continuously for eight seasons from the 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 pot^{-1} in the continuous aerobic rice soil increased the vegetative growth parameters, chlorophyll meter readings, and above-ground 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, B. 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 IRRI farm: an aerobic field where aerobic rice has been grown continuously for 11 seasons from the 2001 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 the 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 above-ground N uptake of plants fertilized with ammonium sulfate were relatively higher than those fertilized with urea, when the N rate was above 0.6 gN pot^{-1}. Furthermore, the differences in these parameters between ammonium sulfate and urea applications increased as the N rate increased. Additional pot experiments using the continuous aerobic soil were 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 N efficient genotypes in combination with improved N management strategies.

Xiao Qin Dai, Hong Yan Zhang, J. H. J. Spiertz, Jun Yu, Guang Hui Xie, B. A. M Bouman. (In preparation 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. Considerable 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 not only 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 a standard NPK dose, a PK dose (N omission), an NK dose (P omission), an NP dose (K omission) and a control with no fertilizer input. Omission of N reduced yield by 0.5~0.8 $Mgha^{-1}$ for aerobic rice and 2.3~4.3 $Mgha^{-1}$ 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 omission of N, P and K, respectively, in the AR-WW sequence and by 30, 6 and 0% for omission of N, P and K, respectively, 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 in the WW-AR sequence. Generally, omission 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 to 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.

Xie Guanghui, Yu Jun, Wang Huaqi, B.A.M. Bouman. 2008. Progress and yield bottleneck of aerobic rice in the North China Plain: A case study of varieties Handao 297 and Handao 502. *Agricultural Sciences in China* 7(6): 641-646.
DOI 10.1016/S1671-2927(08)60097-8

Abstract
Aerobic rice has been considered a promising rice cultivation system as water scarcity is increasing in the world. This article summarizes the advances in aerobic rice management researches in the North China Plain, focusing on yield formation and its bottlenecks. High-yielding and good-quality aerobic rice varieties adapted to aerobic soil conditions have been released officially and adopted by farmers in North China. The varieties Handao 502 and Handao 297 have been recognized as the most promising varieties reaching a yield level of 3.5 - 5.0 tha^{-1} with 450 - 650 mm water input. Compared with lowland rice, water input in aerobic rice was more than 50% lower, and water productivity was 60% higher. Researches on responses of rice cultivars to nitrate N and ammonium N supplied at early growth stages provided the first evidence for a preference of aerobic rice HD297 for nitrate N supply, compared with responses of the lowland rice variety. Zinc uptake studies demonstrated that introduction of aerobic rice system on calcareous soils may increase zinc deficiency problems. Sink size was identified as the limitation of aerobic rice yield, because its spikelet number m^{-2} was too low (20,000 - 24,000) compared with the lowland rice. For future research, more attention is suggested to be paid to yield formation focusing on effects of water regimes on tiller dynamics. Understanding of nutrient uptake and response to fertilization effects are also urgently required to establish optimized crop management technology. Additionally, alternative cropping systems based on aerobic rice should be established, and key sustainability and environmental impact issues in the systems need identified.

Xue Changying, Yang Xiaoguang, B.A.M. Bouman, Deng Wei, Zhang Qiuping, Yan Weixiong, Zhang Tianyi, Rouzi Aji, Wang Huaqi, Wang Pu. 2008. Effects of irrigation and nitrogen on the performance of aerobic rice in northern China. *Journal of Integrative Plant Biology* 50: 1589-1600.
DOI 10.1111/j.1744-7909.2008.00771.x

Abstract
Aerobic rice is a new production system in which specially developed varieties are grown under non-flooded, non-puddled, 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 the 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 tha^{-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 the total amount of water applied. High yields coincided with a 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 1,000-grain weight. There were no or inconsistent interactions between water and N. With the highest water application, five splits of N gave higher yields than three splits, whereas three splits gave higher yields 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 3 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 Quiping, Yan Weixiong, Zhang Tianyi. 2008. Optimizing yield, water requirements, and water productivity of aerobic rice for the North China Plain. *Irrigation Science* 26:459-473.
DOI 10.1007/s00271-008-0107-2

Abstract
Water resources for agriculture 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 non-flooded and nonsaturated aerobic soil, just like wheat and maize. Although an estimated 80,000 ha are cultivated with 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, from 2002 to 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 productiveness. On typical freely draining soils of the North China Plain, aerobic rice yields can reach 6 - 6.8 tha^{-1}, with a total water input ranging between 589 and 797 (rainfall = 477 mm and water application = 112 - 320 mm). For efficient water uses, 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 was 458-483 mm. The water productivity with respect to total water input (irrigation plus rainfall) was 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 tha^{-1} and beyond. Further research is needed to determine whether the panicle (sink) size is large enough to support such yields and/or whether improved management is needed.

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About this Impact Assessment

Rice, a staple food for over 70% of Asians, is also the single biggest user of water, requiring 2-3 times more input (irrigation plus rain) water per unit of grain produced than crops such as wheat and maize. With growing populations, increased urbanisation and environmental degradation, the supply of fresh water is depleting. Recognising the water constraints to rice yield, the aim of the project entitled '*Developing a System of Temperate and Tropical Aerobic Rice (STAR) in Asia*' was to develop water-efficient aerobic rice technologies. This paper highlights the success of that project.

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