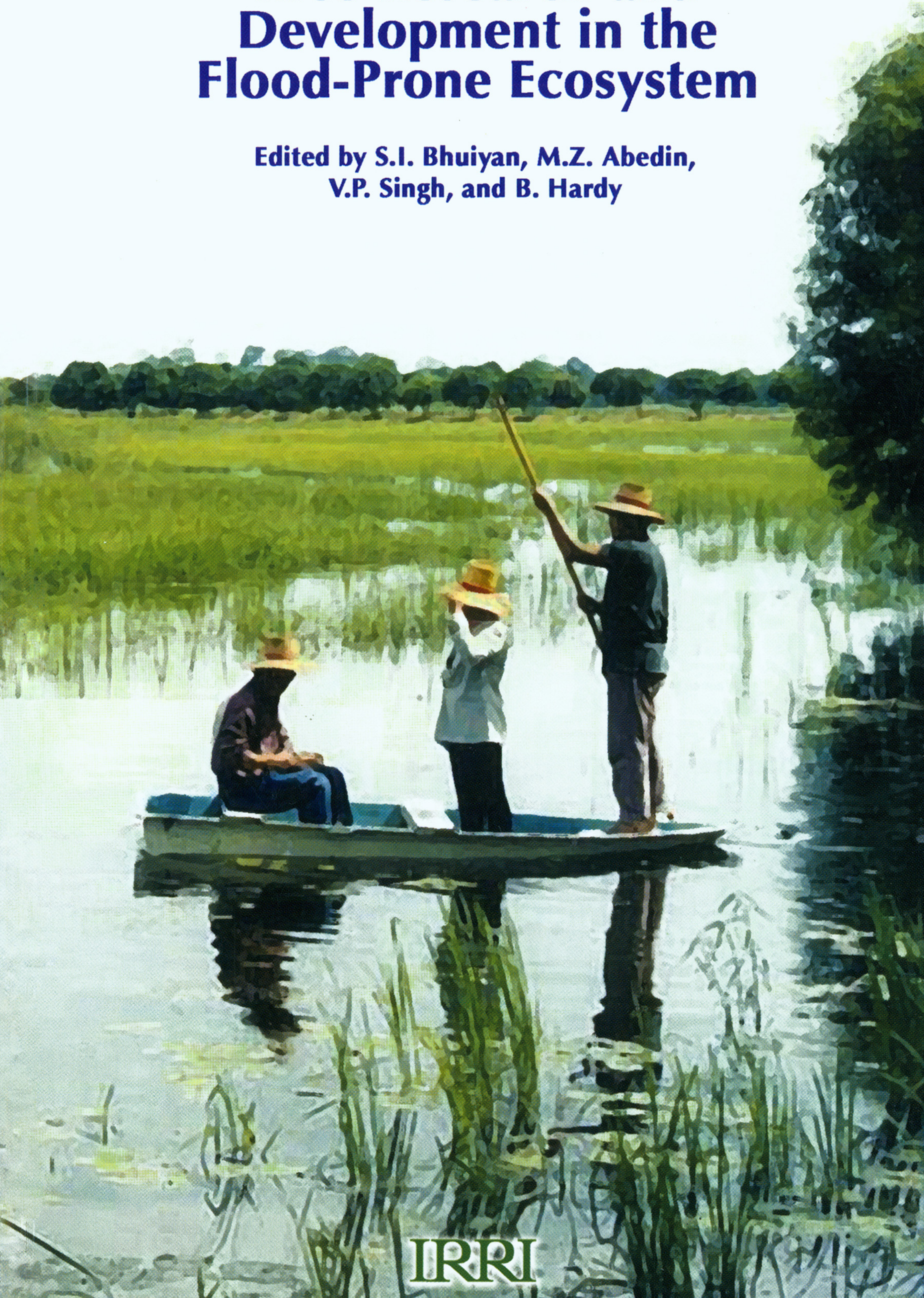
Rice Research and Development in the Flood-Prone Ecosystem

Edited by S.I. Bhuiyan, M.Z. Abedin,
V.P. Singh, and B. Hardy



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Foreword

The flood-prone ecosystem consists of the depressed basins and lowland areas adjacent to rivers in the deltas of humid and subhumid tropics and in the coastal areas subject to flooding caused by tidal fluctuations. This ecosystem is important for many rice-producing countries, particularly in South and Southeast Asia, where more than 11 million hectares are prone to uncontrolled flooding. Rice is the predominant crop in this ecosystem. Globally, the flood-prone ecosystem accounts for about 9% of total rice lands but, for India, Bangladesh, Myanmar, Vietnam, and Thailand, flood-prone rice can represent more than 25% of total rice lands. More than 100 million people in South and Southeast Asia directly depend on this ecosystem for their livelihood. Population density in flood-prone areas is extremely high and productivity is stagnant because of a range of factors.

This ecosystem is a complex environment for rice production because of the various nature, depth, and timing of flooding. Deepwater and floating rice are mainly grown in unbunded fields on the floodplains and deltas of rivers such as the Ganges and Brahmaputra of India and Bangladesh, the Irrawaddy of Myanmar, the Mekong of Vietnam and Cambodia, and the Chao Phraya of Thailand. Flooding occurs in the later stages of plant growth and can last for several months. Tidal wetland rice is cultivated during the wet season in scattered areas along the coastal plains of Bangladesh, India, Indonesia, Myanmar, Thailand, and Vietnam. Salt-tolerant tidal rice is grown in areas that have salt-water intrusion from the sea. Though rice research has helped alleviate poverty and improve food security for the areas endowed with irrigation and other improvements, modern rice technologies have yet to make a strong impact. Strategic research is needed so that constraints to increased rice production from droughts, floods, waterlogging, salinity, weeds, pests, and diseases can be minimized.

There are many opportunities for increasing rice yield in the flood-prone ecosystem. Among the priorities are the development of higher-yielding short- and medium-duration varieties with tolerance of submergence, delayed planting, and cold temperature at the seedling stage for the boro season, and tolerance of flooding during germination in areas where direct seeding is practiced. The development and/or validation of crop and natural resource management strategies are needed to explore the genetic potential of improved cultivars. It is also important to improve stand establishment with early flooding or low temperature and pre- and post-submergence management. The development of appropriate farming systems incorporating nonrice crops and fisheries can ensure the efficient use of resources and improve farmers' income. Research on socioeconomic aspects is required to determine research needs, assess the impacts of new strategies, and determine gaps and emerging challenges. A participatory approach to technology development and transfer can accelerate the achievement of impact.

In recent years, rice research has succeeded in developing improved cultivars and resource management practices appropriate to some flood-prone environments. Varieties with higher yield and the traditional capacity to elongate above deep water have been developed. Improved short-season cultivars have been developed for the tidal wetlands. Crop management strategies and materials developed from research conducted under complementary initiatives among IRRI and national agricultural research and extension systems (NARES) are providing other opportunities for increasing the productivity of land, water, and labor in this ecosystem.

IRRI, with financial support from the International Fund for Agricultural Development (IFAD) and in collaboration with the Bangladesh Rice Research Institute (BRRI), organized an international workshop on Rice Research and Development in the Flood-Prone Rice Lands of South and Southeast Asia on 9–11 January 2001 in Gazipur, Bangladesh. The participants discussed the hydrological, biological, agronomic, and socioeconomic perspectives of flood-prone rice environments; the challenges, potentials, and strategies for increasing the productivity of rice lands in flood-prone environments; and issues and strategies for action. IRRI and its partners in the NARES in India, Bangladesh, Sri Lanka, Thailand, and Vietnam agreed to initiate collaborative activities to validate and transfer potential improved technologies for the flood-prone ecosystem to improve the well-being of the people in it.

This publication contains the papers presented at the workshop and the major recommendations arrived at during the discussions held. We hope that this will be an important source of information for scientists and development workers who are interested in improving the livelihood of the people in it.

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Many people contributed to the success of the workshop and helped to publish this book. We are grateful to Dr. N.I. Bhuiyan, director general of the Bangladesh Rice Research Institute (BRRI), Dr. A.R. Gomosta, director of research, BRRI, and Dr. Hamid Miah, IRRI liaison officer in Bangladesh, for their inspiration and support in organizing the workshop. Dr. Bhuiyan and Dr. Gomosta helped review some of the papers. We are pleased to acknowledge the contribution of Dr. Mahabub Hossain, head of IRRI's Social Sciences Division, for his guidance in organizing the workshop and publishing the proceedings. He took initiative to review the papers to contribute to writing the overview of the proceedings. We also thank Mr. Azad Choudhury and many other staff in the IRRI-Bangladesh office for providing technical support in managing the workshop and in reproducing papers, and M. Romilee Bool of IRRI's Social Sciences Division for her assistance in bringing out this publication. Financial assistance received from the International Fund for Agricultural Development (IFAD) for organizing the workshop and for publishing the proceedings through TAG 424 is gratefully acknowledged.

Rice research and development in the flood-prone ecosystem: an overview

M. Hossain and M.Z. Abedin

Ecosystem variation and cultivar diversity

The flood-prone ecosystem in South and Southeast Asia is characterized by a great diversity of growing conditions, such as in amount and duration of rainfall, depth and duration of flooding, frequency and time of flooding, time and duration of drought, soil type, and topography. More than 20 million ha of rice lands in South and Southeast Asia undergo flooding and more than 100 million people live and make their living in the flood-prone ecosystem. Flooding conditions vary from submergence of 1 to 10 days to stagnant water of varying depth for up to 6 months. Daily submergence caused by tidal fluctuations is also another form of flooding that affects crop production. In general, flood-prone rice lands include rainfed shallow submergence-prone and medium-deep waterlogged lowlands, deepwater areas, and tidal wetlands (IRRI 1984). Hossain et al, Miah et al, Thakur, Salam et al, Singh et al (all in this volume), and Catling (1992) have provided a detailed description of flood-prone areas in individual countries.

It is difficult to delineate this ecosystem precisely. Considering the availability of data, Huke and Huke (1997) defined "deepwater" areas as those with a depth of flooding of more than 1 m during the peak of the monsoon season and "intermediate deepwater" areas as the land with a flooding depth from 30 to 100 cm. Using this definition, they established that, in the late 1970s, about 13.5% of Asian rice areas could be categorized as "flood-prone." The area decreased marginally to about 12% by the mid-1990s (Huke 1982, Huke and Huke 1997). But, in several countries in Asia, this ecosystem accounts for a large proportion of rice areas. In Bangladesh, for example, by the mid-1990s, nearly 27% of the rice areas were categorized as "intermediate deepwater" and another 11% as "deepwater."

Production systems in flood-prone areas usually include rice during the monsoon period and upland crops or a fallow period during the dry season. Crop productivity and income are usually very low vis-à-vis environments favorable to growing modern varieties of rice. Management interventions over the last decades have transformed much of the flood-prone ecosystem into areas favorable for growing a rice crop during the whole year or at least during the dry season. The availability of high-yielding modern varieties; flood control mechanisms such as dikes, sluices, and polders; and irrigation and drainage facilities has helped to bring about these changes. This resulted in changed cropping patterns, biological diversity, and livelihood patterns within the flood-prone ecosystem.

Because of varying ecological and cultural conditions, the flood-prone ecosystem harbors a large diversity of rice cultivars. This diversity provides the base for rice improvement, either through pure-line selection or by involving cultivars in hybridization as parents. Singh et al describe the major cultural types and popular varieties in different states of eastern India. In eastern Uttar Pradesh, about 200,000 ha of rice land suffer from flash flooding, where varieties Madhukar and Bar Avarodhi are grown because of their ability to survive under complete submergence for 7 to 10 days. For areas that remain submerged for at least 30 days, Jalpriya and Chakia 59 are grown. These varieties are photoperiod-sensitive, flower in the third week of October, and mature in 140 to 170 days. In West Bengal, about 70% of the estimated 0.46 million ha of flood-prone rice land has a flooding depth of 50 to 70 cm. Bhasamanik, Kalma, Gochi, Meghr, Sadamota, Panikulash, and Achra are popular rice varieties for this ecosystem. These varieties have excellent elongation ability and have short bold grains with red kernels. Jaladhi, Digha, Khalirai, and Jalprabha are popular varieties for areas that are flooded at a depth of more than 100 cm.

Singh et al also classify traditional cultivars by elongation and kneeing ability, submergence and drought tolerance, resistance to ufra, which is a major disease for this ecosystem, and tolerance of problem soils such as those having P and Zn deficiency, salinity and alkalinity, and iron toxicity. Some cultivars that have multiple valuable traits are Jalmagna and Jalnidhi, of the Rayada class of varieties having good resistance to ufra; and Pokali, Damodar, and Dasal, which tolerate salinity and P and Zn deficiency.

Bashar et al describe the ecological variation and cultivar diversity for the flood-prone ecosystem in Bangladesh. In Khulna and Jessore areas with shallow flooding depth, the popular variety is the Rayada group, which tolerates cool temperature during the seedling stage, and is strongly photoperiod-sensitive with flowering in late September to early October. But, unlike other deepwater rice varieties, Rayada plants do not have seed dormancy. In the deeply flooded areas of Dhaka, Tangail, Pabna, and Faridpur districts, the most popular varieties are the Digha group, whereas, in the depressed basins of Sylhet, the popular varieties are the Laki group. Deepwater rice germplasm has been characterized for resistance to different diseases and insects. The Rayada group is resistant to ufra; Laxman jota to tungro virus; Khama and Ghumsi to bacterial blight; Kalamanik, Dudbazal, and Sada Pankaich to sheath blight; the Bazal group to brown planthopper; and Malia Bhangar to stem borer.

Constraints to and strategies for increasing rice productivity in the floodprone ecosystem

Rice production in the flood-prone ecosystem suffers from multiple constraints—biotic, abiotic, social, and economic. Miah et al group such constraints into physical (abiotic) and biological (biotic) ones. Abiotic constraints include varying degrees of submergence marked by its timing, frequency, and duration. The level of turbidity also poses an additional dimension of submergence. Declining soil fertility, primarily caused by reduced organic matter content, is also mentioned as a constraint. Drought at different crop growth stages is a limiting factor in some areas. Gregorio et al mention that soil and water management is also difficult in flood-prone areas.

Among biotic stresses, Miah et al report that the lack of high-yielding varieties that can tolerate a range of biotic stresses is the major constraint. They listed such capabilities as

- submergence tolerance, tall seedlings, sturdy culms, moderate tillering, and photoperiod sensitivity
- drought tolerance at the seedling stage, rapid internode elongation ability, kneeing ability, photoperiod sensitivity, and high panicle density and high panicle weight for good yields
- tolerance against major diseases
- responsiveness to improved technologies
- capability to withstand frequent natural hazards posed by flood and drought

The nature of flooding, particularly in areas without any flood control mechanisms, makes rice production and economic returns risk-prone and even uncertain. These contribute to poverty and reduced food security at the household and community level. Farmers in most of these areas developed their own ways of dealing with such risk and uncertainty, for example, with variety selection, stand establishment, crop management, and improved farming systems.

Germplasm enhancement

There is no denying the fact that germplasm improvement is very important for increasing the productivity of rice in the flood-prone ecosystem. However, both Gregorio et al and Thakur opine that improving the genetic potential of the traditional varieties grown in the flood-prone ecosystem and breeding new varieties for such areas are very difficult, particularly for the deepwater environment. Gregorio et al suggest that current knowledge about interactions between soil- and water-related stresses is limited. Although the physiological mechanisms of submergence tolerance and elongation ability of rice are known, their functions and expressions under different soil conditions are still a mystery. Understanding the mechanisms of their inheritance is a prerequisite to sound breeding strategies.

Thakur explains that the breeding strategies for flood-prone rice should at least include careful consideration of elongation ability of deepwater rice, photoperiod sensitivity, and submergence tolerance. Scientists agree that a quantum jump in yield is still difficult and, therefore, developing varieties with higher but more stable yields and wider adaptability should be a realistic goal in germplasm enhancement until frontiers of science show new opportunities. Gregorio et al suggest that recent developments in biotechnology provide tools for accelerating breeding progress, increasing selection efficiency at lower costs, and transferring genes across species and genetic barriers.

Islam evaluates the experience with varietal improvement for deepwater rice in Bangladesh, which began in 1917. During the pre-Green Revolution era, nine varieties from pure-line selection and two from the hybridization program were released. Since the early 1970s, crosses between local deepwater rice varieties and high-yielding semidwarf modern varieties (IR8, TKM6) have been made, but success has not been attained in developing and releasing any variety. Islam recommends that a breeding strategy for this ecosystem should be limited to pure-line selection and/or hybridization and should aim for modest yield improvement. Breeders should target major deepwater rice areas, collect popular varieties, improve them through pure-line selection, and then return seeds of improved varieties to farmers.

Mandal et al characterize the environment in the flash-flood ecosystem in the northern region of Bangladesh and evaluate strategies for increasing rice productivity. Most of the region is monocropped, with rice occupying more than four-fifths of the cropped area. About two-thirds of the area is cropped with low-yielding traditional varieties. The high-yielding modern varieties can be planted in the dry season, but, since the crop is planted late to avoid cold injury, the risk of harvest failure from flash floods in April is very high. The breeding strategy should be to develop short-maturity varieties with cold tolerance at the seedling stage. Mandal et al suggest that water management interventions should be made along with breeding improved varieties to increase rice productivity in this ecosystem. Damage to crops by flash flood can be minimized by constructing submersible embankments with adequate provision for drainage and navigation. The responsibility for the operation and maintenance of embankments should be entrusted to farmers' organizations, which should be encouraged to plant trees along submersible embankments to reduce erosion and thereby minimize the cost of repair and maintenance of the embankments.

Salam et al describe the strategies that need to be adopted to increase rice productivity in different subecosystems existing within shallow-/medium-flooded areas (flooding up to 90 cm) in Bangladesh. Such variability includes flash flooding, medium-deep stagnant flooding, and shallow flooding. They elaborate the constraints to increased rice production in each subecosystem and the breeding strategies needed. The flash-flood areas are characterized by sudden submergence for more than 10 d and uncertainty of the timing of flash flood. The development of varieties with a capacity to tolerate prolonged submergence and having fast recovery after submergence is a suggested strategy. Rice production in the shallow, stagnant flooded areas is characterized by poor crop establishment because of submergence at transplanting, reduced tillering due to a prolonged period of waterlogging, and vulnerability of the crop to submergence at any time of the vegetative growth phase. Breeding strategies should include finding improved germplasm with taller seedlings, photoperiod sensitivity, a sturdy stem, and good tillering under waterlogged conditions.

For the breeding approach, pure-line selection is the traditional practice, which takes a long time. Success to date has been negligible. Scientists pursued hybridization, but success was limited in a few countries only. It has to be noted that, using conventional breeding methods, it takes about 10–12 years to develop a variety. The use of tissue culture can allow somaclonal variation and in vitro selection, which can reduce the breeding cycle to 3–4 years. Gregorio et al also argue that selection efficiency is reduced in traditional breeding as scientists have to depend on phenotypic expression of genes, particularly when interaction occurs. Gene pyramiding for multiple traits and enhanced adaptability cannot be undertaken under conventional breeding. With the use of marker-assisted selection (MAS), a molecular biology technique, breeders can detect alleles of interest rapidly. Most of the current problems of breeding rice for the flood-prone ecosystem could be overcome by using the MAS technique as it is not affected by environmental factors.

Both Thakur and Gregorio et al also agree that farmer participatory breeding can be used as another approach to accelerate the development of varieties acceptable to farmers. The combination of MAS in early generations (F_2 or F_3) and selection by farmers subsequently using their own selection criteria will increase breeding efficiency. This may speed up adoption as it produces varieties specific to a location since the target traits for flood-prone rice areas are not only elongation ability or submergence tolerance but also tolerance of other biotic and abiotic stresses, which are usually specific to a subecosystem. They believe that active partnership among farmers, breeders, agronomists, physiologists, geneticists, social scientists, and other stakeholders is essential for the successful development and rapid dissemination of rice varieties for the flood-prone ecosystem.

Despite the difficulties, considerable achievements have been made. IRRI’s work on germplasm improvement focuses on prebreeding research, including the use of MAS, on flood tolerance, and on providing improved breeding materials to the national agricultural research and extension system (NARES). With such collaboration, the Rice Research Institute of Thailand produced two new plant type lines, HTAAFR810442-B-7-1 and HTAFR84038-B-5-0-1, which have yielded 5.0 t ha^{-1} vis-à-vis 3.7 t ha^{-1} of the local check. The yield of prototype deepwater rice lines was also almost double that of the traditional plant types. Gregorio et al report that the new deepwater line IR62364-2B-10-2-2 yielded about 6 t ha^{-1}, demonstrating that the new plant type yield is comparable with that of modern varieties of irrigated rice for areas with flooding up to about 90 cm.

Thakur has reported that some popular varieties such as Sabita in West Bengal, Vaidehi in Bihar, and Jalnidhi are examples of success for the deepwater ecosystem. RD 19, derived from crosses between IR262-43-8-11 and Pin Gaew, has been recommended for a similar environment in Thailand. Several varieties have been released for semideepwater environments in India, such as Manindra and Jogen in West Bengal, Jalapriya and Bar Avaradhi in Uttar Pradesh, and LPR 96-10-1 and LPR 96-12 in Assam. However, a dependable assessment of their adoption is not yet available.

Salam et al describe the progress made in breeding for the shallow-flooded deepwater subecosystem in Bangladesh. The breeding strategies have been to (1) select early generation progeny with slow elongation at up to 100-cm flooding depth, (2) test combining ability for slow-elongating genotypes with high-yielding materials in the breeding program, and (3) evaluate improved lines in the shallow-flooded areas of the Ganges, Jamuna, and Meghna floodplains. Several improved lines were identified that yielded more than 4.0 t ha^{-1} and could withstand submergence with slow stem elongation. The highest-yielding and most stable advanced line is PCR89114-B-R-2-2-2-1, with an average yield of 2.09 t ha^{-1} in farmers' fields.

Research on crop management

Crop establishment

Successful crop establishment determines the productivity of rice to a great extent. Singh et al reviewed research results and farmers' practices for improving crop productivity through appropriate methods of crop establishment. They discussed the two major methods practiced—direct seeding and transplanting. Several variants within each method have evolved through years of empirical research and farmers' practices. These practices are highly dependent on the rainfall pattern, the internal and surface drainage characteristics of the land, and, to some degree, the socioeconomic conditions of farmers. They described two types of direct-seeding methods: dry or wet seeding—the former being adopted extensively by farmers in South and Southeast Asia. Each one has its advantages and disadvantages. Dry seeding is done by either broadcasting on dry or wet soil or by drilling or dibbling. For transplanting, the use of conventional seedbed-propagated seedlings is most common. Clonal tillers or dapog-raised seedlings are used in specific situations. Among the factors affecting crop establishment, timely seeding and transplanting are crucial. Adjusting seed rate and dibbling of the seeds in direct seeding, the use of healthy seedlings produced through lower seeding densities in the nursery, nursery fertilization with N, and hardening and conditioning of seedlings and their proper handling before transplanting contribute to successful crop establishment and eventually to improved productivity.

Gomosta argues that the quality of crop establishment in the flood-prone ecosystem depends on climatic and edaphic factors, plant biology, and hydrology of the system. The performance of broadcasting or transplanting would depend on specific circumstances. He cites from research conducted in Bangladesh that initial seedling densities ranging from 50 to 350 plants m^{-2} had little effect on optimum yield level and that ultimate crop stand varies because of the addition of nodal tillers or loss of basal tillers but his own research work contradicted these findings. He also describes the potential benefit of ratooning of deepwater rice planted in the dry season of November or December as a boro crop. Results from India suggest that many deepwater rice crops are capable of producing a good crop during the boro season and a ratoon crop during the following wet season.

Crop establishment in areas affected by flood where either the previously established crop has been damaged or crop establishment was not possible before the flood is also a challenging task. Successful crop establishment in such areas after the recession of flood water is very important for food security at the household and national levels. Some farmers in Bangladesh use tillers collected from other unaffected fields to transplant in the fields where flood water has just receded. This requires varieties with high photosensitivity and good capability of regrowth. While farmers use local varieties for such a situation, Gomosta mentions that scientists were able to establish BR22 and BR23, two modern varieties, under similar conditions and obtained a grain yield of about 4 t ha^{-1}.

It has to be noted that, in deepwater rice areas, farmers diversify risk and uncertainty through a range of mixed cropping practices, such as aus rice + DWR, mung bean + DWR, small millets + DWR, etc. Such intercropping practices increase production and income and also provide some food or cash earlier in the season for small farmers, as the harvesting of DWR takes a long time. Finding an appropriate crop mix and space arrangements, selecting appropriate varieties for such intercropping practices, and developing management practices are important for stand establishment.

Weed management

Both aquatic and terrestrial weeds affect rice cultivation in the flood-prone ecosystem. The weed species and their population differ as environment and crop production practices differ. Ahmed and Jabbar describe weed infestation and various aspects of weed management in the flood-prone areas of Bangladesh. *Echinochloa colona*, *Cynodon dactylon*, *Leersia hexandra*, *Cyperus iria*, and wild rice, etc., are major weed species found to be associated with deepwater rice. Wild rice is considered the most notorious. These authors argue that good weed management is essential for good stand establishment and this ensures healthy seedlings having ability to cope with rising floodwater or even flash flood. Farmers may lose 30–40% of their crops, or even more, if they do not properly and timely control weeds. Water hyacinth is a major floating aquatic weed. Establishing live barriers with crops such as jute and *Sesbania aculeata* is often used to control water hyacinth. Ahmed and Jabbar also recommend future directions for research on weed management and highlight the importance of cultural aspects of weed management.

Nutrient management

Floods usually enrich rice lands in the form of silts they carry. Such enrichment is very helpful for farmers as it does not cost anything. Panaullah et al mention that almost everywhere these sediments were compatible with normally expected soil fertility indices and they contain a good amount of organic matter and substantial amounts of N, P, K, S, Ca, Mg, Fe, Mn, Zn, and B. However, recent flood management measures have reduced the amount of silt, and therefore the nutrients, they deposit in flood-prone rice lands. While Gregorio et al suggest that nutrient management in deepwater rice is difficult, Panaullah et al suggest that fertilizer recommendations for different rice-based cropping systems in the flood-prone ecosystem be based on regular sediment and soil tests to avoid overapplication of fertilizer.

Pest and disease management

Islam and Catling report that deepwater rice hosts a large complex of arthropods (74 insects, one crab, and a snail) and three vertebrates (two rats and a bird). More than 40 species of parasitoids and a similar number of arthropod predators were also identified from DWR fields. Among the pest complex, yellow stem borer (*Scirpophaga incertulas*), bandicoot rats (*Bandicoota bengalensis* and *B. indica*), and rice hispa are major pests. These authors have indicated that the pest complex has changed where boro rice is grown in deepwater areas. They also discuss management options for the major pests and future strategies.

Mia and Nahar describe the importance of diseases in rice production in the flood-prone ecosystem. Among the diseases, ufra, sheath blight, blast, and tungro are the most important ones causing considerable yield losses, which can vary depending on disease severity. Yield loss can reach 100% in some cases. These authors indicate that sheath blight can cause up to 31% yield loss, and blast 11-46% loss. The authors also discuss management approaches that can be used in dealing with these diseases.

Increasing productivity of the flood-prone ecosystem

Adoption of modern rice technologies in flood-prone areas

In contrast to the favorable environment for rice production, the adoption of modern varieties and improved cultivation methods is very low in flood-prone areas. In Bangladesh, for example, the adoption of modern varieties in the boro season is about 94% and in the transplanted aman season about 48% (Miah et al), whereas in the flood-prone ecosystem adoption is very low. There is no adoption of modern varieties in the deepwater ecosystem in Bangladesh because of the lack of such varieties and flood-prone transplanted aman areas have about a 10% adoption of modern varieties.

Impact on productivity

Since success in increasing productivity for deepwater rice plants has remained limited, despite substantial past efforts, a better strategy for improving the livelihood of the people living in the ecosystem should be to explore the potential for crop diversification and intensification through innovative and improved management strategies. This is possibly more important in areas where cropping intensity has declined and crop diversification has diminished because of the cultivation of boro rice as an alternative to deepwater rice, replacing a range of upland crops.

Hossain et al document the change in agriculture and livelihoods in the ecosystem during the 1990s with primary data obtained from repeat household surveys. The authors note that, during the dry season, the flood-prone ecosystem becomes highly favorable for growing modern varieties with easy availability of water for low-cost irrigation and highly fertile soils because of the regular siltation from flooding that ensures high yields. In Bangladesh, the area under traditional deepwater rice varieties has declined from 2.09 million ha in 1969-70 to 0.78 million ha in 1999-2000, as farmers replaced the long-duration, low-yielding risky deepwater rice cultivars with the modern, high-yielding safe boro rice varieties grown during the dry season. This change has contributed to a respectable growth in rice yield, similar to that of favorable ecosystems. The farmers have also been able to substantially increase their income through engagement in rural nonfarm activities—business, services, construction labor, and transport operations—thereby easing the poverty situation. Hossain et al argue that, since a large proportion of the land remains single-cropped, options to introduce a double-rice cropping system should be explored by developing shorter-duration and cold-tolerant boro varieties that would allow cultivation of traditional deepwater rice after the harvesting of boro rice.

The integration of deepwater rice with boro rice is another option to increase crop productivity in traditional deepwater rice areas. Deepwater rice could be either relay-cropped with the boro rice crop or sown after the harvest of boro rice. Short-duration varieties for boro rice, choice of the right variety for deepwater rice, minimum tillage techniques, the use of sprouted seeds, appropriate nutrient management, etc., are important issues for such integration.

The breeding and agronomic management strategy should consider intensification as well as diversification of the farming system in flood-prone areas along with increasing the productivity of the rice crop. Elahi and Khan describe opportunities for crop diversification in the flood-prone ecosystem in Bangladesh. They argue that opportunities exist for introducing a nonrice crop in the dry season in the existing rice-fallow or rice-rice cropping pattern on about 1 million ha of deepwater rice land. The exploitation of this potential will require farmer participatory demonstrations by researchers and extension agents. On another 0.72 million ha, farmers are already cultivating wheat, potato, mustard, and other rabi crops, but their yields are low. Attempts should be made to improve the yield of the nonrice crops through farmer participatory demonstrations of modern management packages.

It is very important to see that the livelihood of the farming community in the flood-prone ecosystem is improved through improvement of the farming system. This requires an approach that integrates crops, livestock, fisheries, and fruit and other trees. Hussain et al consider rice-fish culture as an ideal method of land use since the land can be used for production of both rice and fish, either concurrently or in sequence. This practice is gaining popularity among many farmers in South and Southeast Asia. Field trials in Bangladesh showed that, with appropriate management, farmers can harvest about 400–800 kg of fish per ha of rice area. In good years, production has been even higher. This technology provides an opportunity for increasing income and it provides better access to fish, an important source of protein for the resource-poor farmers in flood-prone areas.

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Increasing the productivity of the flood-prone ecosystem

Changes in agriculture and the economy in the flood-prone environment in Bangladesh, 1988 to 2000: insights from a repeat survey of 16 villages

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Semidwarf modern rice varieties are not suitable for the flood-prone environment. So, a general perception exists that the Green Revolution bypassed this ecosystem, which constitutes about 40% of the rice land in Bangladesh. This paper assesses the changes in agriculture and the economy in the flood-prone ecosystem by analyzing household-level data collected through a sample survey of villages conducted in 1988 and 2000. The findings show that, although farmers still grow mostly traditional varieties during the wet season, the coverage of modern varieties during the dry season when flooding is not a problem has expanded from 43% in 1988 to 80% during 2000. In a large proportion of areas, farmers have abandoned the low-yielding, high-risk traditional rice varieties and shifted to high-yielding modern varieties during the dry season by investing in irrigation through installing shallow tubewells and power pumps. These changes in the cropping pattern have reduced cropping intensity from 174% to 143% of cultivated land, but increased the average rice yield by 66% over the 12-year period. Technological progress and the fast increase in rice supply have contributed to a reduction in the unit cost of rice production, an increase in labor productivity, and a much slower increase in rice prices compared to the general cost of living index. These factors have benefited the rural and urban poor more than farm households. The share of rice farming in rural household income is small and declining, however, because of the small average holding size, which has declined from 0.85 to 0.76 ha over the period. The survey estimates a 3.4% annual increase in household income mostly arising from the expansion of nonfarm activities, which now account for 70% of household income compared with 44% in 1988. The incidence of poverty has declined from 65% to 54%, but the improvement in economic conditions has been more pronounced for households earning their livelihood from services and business than for households relying on farming or agricultural labor.

The flood-prone rice ecosystem can be defined as a rice production environment in which temporary and seasonal flooding constrain the adoption of currently available dwarf and semidwarf modern rice varieties. The planners of the International Rice Research Institute (IRRI) recognized as early as 1978 that the improved rice technology now available has little advantage over farmers' technology in areas of deep or

Table 1. Importance of the flood-prone ecosystem in Asia (% of rice area).

Country	Flooding depth				Total flood-prone	
	(30–100 cm)		(>100 cm)			
	1978-80	Mid-1990s	1978-80	Mid-1990s	1978-80	Mid-1990s
Bangladesh	25.8	26.9	11.1	11.4	36.9	38.3
Cambodia	44.3	18.4	7.1	8.0	51.4	26.4
India	11.5	10.5	6.2	3.2	17.7	13.7
Thailand	11.5	18.4	4.6	3.5	16.1	21.9
Vietnam	17.6	10.2	7.6	2.8	25.2	13.0
Asia	9.6	9.2	3.9	2.8	13.5	12.0

Source: Huke and Huke (1997).

intermediate water depths. In such areas, dwarf rice varieties cannot yield as much as traditional varieties and little in the way of improved cropping pattern has been suggested for them (IRRI 1979). There is therefore widespread concern that the Green Revolution in rice cultivation, which brought dramatic increases in the rice supply and changed socioeconomic conditions in rural Asia over the last three decades, might not have benefited the people living in the flood-prone rice ecosystem much (Catling 1994).

It is difficult to delineate this ecosystem precisely. Huke and Huke (1997) defined deepwater areas as those with a depth of flooding of more than 1 m during the peak of the monsoon season, and intermediate deepwater as the land with a flooding depth from 30 to 100 cm. Using this definition, they established that in the late 1970s about 13.5% of the rice area in Asia could be categorized as flood-prone. The area was reduced marginally to about 12% by the mid-1990s (Huke 1982, Huke and Huke 1997). But, in several countries in Asia, this ecosystem accounts for a large proportion of rice area (Table 1). In Bangladesh, for example, by the mid-1990s, nearly 27% of the rice area was categorized as intermediate deepwater and another 11% as deepwater area. These countries therefore cannot ignore the need for crop improvement research for the flood-prone ecosystem to increase food supplies at the national level and to improve the livelihood of the people living in the ecosystem.

Although researchers have had limited success in developing suitable high-yielding modern rice varieties for the flood-prone ecosystem, it is *not* a valid observation that the Green Revolution has completely bypassed this ecosystem. Excessive standing water is only a seasonal phenomenon for such areas, with flooding duration of 3 to 7 months. During the dry season (from November to May), these areas become highly favorable for growing modern varieties with easy availability of water for low-cost irrigation and highly fertile soils because of regular siltation from flooding that ensures high yields. In the Mekong River Delta in Vietnam, heavy investment in flood control and drainage was instrumental in transforming the flood-prone ecosystem into a highly favorable environment where farmers have abandoned growing

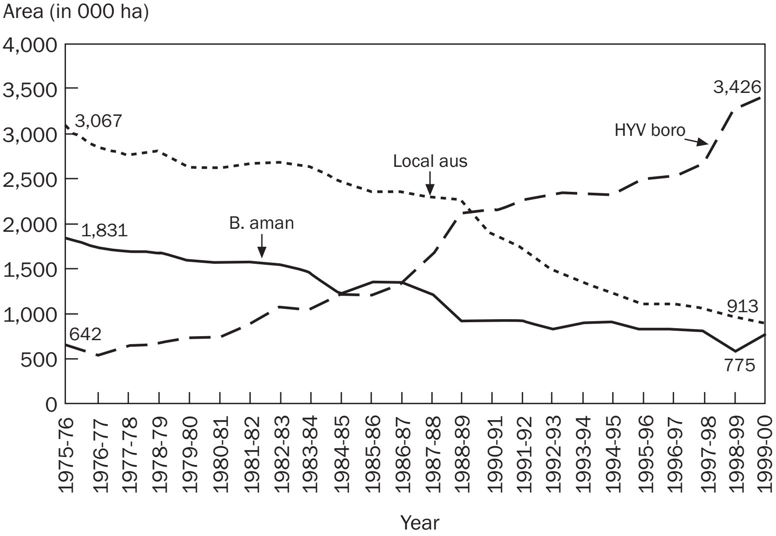

Fig. 1. Changes in area under aus, deepwater aman, and boro, 1975-76 to 1999-2000.

traditional long-duration deepwater rice in favor of two short-duration high-yielding varieties. This change has contributed to an increase in rice yield from 2.5 to 10.0 t ha^{-1} per year (Hossain et al 1995). A similar change has also occurred in many other countries (Catling 1994). In Bangladesh, the area under the traditional broadcast aman rice grown in the flood-prone ecosystem has decreased from 1.84 to 0.78 million ha from 1973-74 to 1999-2000, as farmers replaced the traditional long-duration aman varieties with modern high-yielding boro varieties grown during the dry season (Fig. 1).

The objective of this paper is to assess the changes in the livelihood system of the people in the flood-prone ecosystem in Bangladesh over the last decade when Bangladesh experienced a rapid growth in rice production through technological progress. The paper seeks answers to the following questions: How important are agriculture and rice production as a source of livelihood for the people in the flood-prone environment? What has been the magnitude of change from deepwater aman to boro cultivation and what has been the effect of this on rice production and farm income? Has the limitation on the adoption of improved technology in the monsoon season constrained overall socioeconomic development in the flood-prone ecosystem? Primary data produced through sample household surveys in 1987-88 and 1999-2000 have been analyzed to answer these questions.

Data and methodology

The benchmark data for the study are drawn from a sample survey conducted in 1987-88 using a multistage random sampling method for the IRRI-sponsored project "Differential Impact of Modern Rice Technology in Favorable and Unfavorable Rice

Production Environments" (David and Otsuka 1994). In the first stage, 64 unions, or village clusters, taking one union each from 64 districts of Bangladesh, were selected from the list of all unions using a random number table. In the second stage, data on land area, total population, and literacy rates were obtained for all villages of the selected unions from the district reports of the 1981 population census. Two villages were selected purposively for each union such that the population pressure and the literacy rate for the selected villages were similar to those for the selected unions. Thus, 128 villages were selected, with the first choice within each pair being the village most representative of the union. A census of all households in the first-choice village was undertaken to collect information on the ownership of land, adoption of modern rice varieties, and the major source of household income. Where the village community was found to be noncooperative for conducting the survey, the second-choice village was included in the sample. Two sites were dropped at this stage because of the problem of logistics for conducting the survey. This nationally representative sample thus consisted of 62 villages from 57 districts.

The census of the selected villages enumerated 9,874 households or 159 households per village. These households were used as the sample frame for the final selection of the sample for data gathering on the operation of the household economy. The households were classified into four land ownership groups: (1) functionally landless (up to 0.2 ha of land), (2) small landowner (0.2 to 1.0 ha), (3) medium landowner (1.0 to 2.0 ha), and (4) large landowner (more than 2.0 ha). Each of the land ownership groups was further classified into two subgroups according to whether the household was engaged in tenancy cultivation or not. Twenty households were then selected from each village using the proportionate random sampling method so that each of the eight (4 × 2) strata was represented according to its weight. The total sample for the 1987 survey consisted of 1,245 households.

The selected households were interviewed with a structured questionnaire to gather data on demographic characteristics of all household members, the use of all parcels of land owned and operated by the households, costs and returns of cultivation of major crops, purchase of inputs and marketing of products, ownership of nonland assets, employment of working members and earnings from nonfarm activities, and the perception of the respondent regarding the economic standing of the household in the village and the changes in its economic conditions. The findings from the 1987-88 survey were published in Hossain et al (1994).

A resurvey was conducted covering the financial year 1999-2000 for 16 of the 62 villages that belonged to the flood-prone ecosystem. The villages where more than 50% of the land was reported as being flooded at a depth of more than 50 cm during the peak of the monsoon season were identified as flood-prone. In the resurvey, the sample was drawn using the classification of households by the wealth ranking method rather than that based on land ownership and land tenure as used in the benchmark study. In consultation with the key informants using the participatory rural appraisal (PRA) methodology, the households in the village were classified into four groups: (1) rich, (2) solvent, (3) self-sufficient, and (4) poor. To ensure that all former sample households and their off-shoots were covered in the present survey, we decided to draw a sample of 30 households from the four groups using the stratified random sampling method. New samples were drawn for the cells that were underrepresented by the sample households selected during the 1987-88 survey. The sample consisted of 320 households for 1987-88 and 485 for the 1999-2000 financial year.

Household income as measured in the study includes income received in cash as well as in kind. A money value was imputed to receipts in kind at prices prevailing in the survey villages. Household consumption of self-produced crops and their by-products and livestock, fishery, and forestry products is considered as income. The income from crop production activities is estimated as the value of the main product and the by-products net of the costs of seeds, fertilizer, pesticides, irrigation charge, payment of hired labor, and rental cost of draft machine power. Rent paid to the landowner and received from tenants was included in the calculation of income, but the cost of own land was not imputed on the grounds that the value of the land is not depreciated by its use. The interest on working capital employed in the activity was not imputed either and was considered as a cost.

Changes in economic activities and socioeconomic conditions were assessed by comparing the mean values of the criterion variables for an average household for the two surveys. A limitation of the study is that it cannot assess the changes in the socioeconomic situation in the flood-prone ecosystem vis-à-vis the favorable irrigated ecosystem that faces no environmental constraints to the adoption of modern technologies.

Results and discussion

Resource base

The change in the endowment of resources for economic activities can be seen from Table 2. As expected, the availability of land, the most important resource for agricultural production, declined under demographic pressure. The average size of land owned declined by 8%, from 0.64 to 0.59 ha, from 1987-88 to 1999-2000. Because of the extreme pressure of population on land, the degree of landlessness is very high in Bangladesh. The functionally landless households, defined as those having up to 0.2 ha of land that cannot be a significant source of income, constituted 49% of all households in 1987-88. Their number has hardly changed since then. Farm households, defined as those that cultivated some land for agricultural production, constituted 62% of the households in 1987-88. This number increased marginally to 64% by 1999-2000.

It is interesting to note that the land available through the tenancy market for the land-poor households increased substantially (63%) over the period. This change was induced by the scarcity of agricultural labor for the land-rich households (see below). The percent of farm households that operate some rented-in land (two-thirds of these tenant farms had some cultivated land of their own) increased from 38% to 58% over the period and the area under tenancy cultivation increased from 20% to

Table 2. Changes in resource base of the households, 1988-2000.

Resource	1988	2000	Percent changes
Own land (ha)	0.64	0.59	–8
Cultivated land (ha)	0.85	0.76	–11
Area under tenancy (%)	19.8	32.2	63
Irrigation coverage (%)	28.1	60.1	114
Modern variety coverage (% of rice area)	20.2	47.2	134
No. of workers	1.76	1.85	5
Average years of schooling for male workers	2.85	4.26	49
Agricultural capital (Tk)	4,361	7,630	75
Nonagricultural capital (Tk)	na[a]	27,413	–
Percent of functionally landless households	49.4	48.7	–1.4
Percent of farm households	62.4	64.2	2.9
Percent of tenant farms	38.3	57.5	50.0

[a] na = not available.

32% of the operated land. The average size of holdings for farm households declined by 11%, from 0.85 to 0.76 ha, over the 1988-2000 period.

The coverage of irrigation and the adoption of modern rice varieties, which are the base for productivity growth of land, have increased substantially over the period. The percent of land with access to irrigation facilities more than doubled, from 28% to 60%, and the rice area covered by modern high-yielding varieties increased from 20% to 47%. These data indicate that a significant portion of the irrigated land is used for growing nonrice crops. The spread of modern varieties (MVs) was limited, however, to rice cultivation during the dry season. The adoption of MVs was marginal during the monsoon season, limited to patches of medium-highlands and highlands.

The endowment of the other factors of production, labor and capital, also increased somewhat during the period. The average number of earners per household increased in spite of a larger proportion of young adults attending schools. This was mainly due to the reduction in the proportion of children in the total population, resulting from the recent progress in birth control. The child-woman ratio, which is the indicator of current fertility, declined from 69% to 49%, and the proportion of the population up to 15 years of age declined from 48% to 39% from 1988 to 2000.

The human capital content of rural labor has also increased. The average years of schooling for male workers increased from 2.85 in 1988 to 4.26 in 2000, an impressive growth of 49%. The improvement in human capital facilitated the expansion of nonfarm economic activities in rural areas (see below). There was an impressive increase also in the accumulation of nonland agricultural assets with increased investment in irrigation equipment and power tillers. However, the rural capital accumulation has been more impressive for undertaking nonfarm activities, such as transport operations and trade and business. In 2000, about 78% of the rural capital (excluding land value) was employed in nonagricultural activities.

Table 3. Changes in cropping system and yield rate.

Crop	Percent of land under the crop		Yield (kg ha^{-1})		
	1987-88	1999-2000	1987-88	1999-2000	Percent change
Rice	127.7	110.0	2,164	3,589	66
Aus TV	30.9	7.3	1,220	1,416	16
B. aman TV	67.6	45.4	1,618	1,842	14
T. aman	1.7	5.3	2,605	3,914	50
Boro	27.5	52.0	4,541	5,386	19
Other crops	45.9	32.5			
Jute	7.1	4.3	1,801	1,891	5
Wheat	6.4	4.8	1,734	2,121	22
Pulses	15.0	9.4	892	852	–4
Oilseeds	6.8	2.3	992	862	–13
Potato	4.3	2.9	10,578	26,741	153
Vegetable	0.9	2.6	6,352	11,621	83
Others	5.4	6.2	–	–	–
Cropping intensity	173.6	142.5	–	–	–

Land use and cropping pattern

The change in the use of land for crop production can be reviewed in Table 3. As expected, the traditional deepwater aman rice was the major crop in the flood-prone ecosystem in 1987-88, occupying nearly two-thirds of the rice land, followed by traditional aus rice, which used to be grown as a mixed crop with broadcast deepwater aman. The productivity of these crops is very low, however, with yields of 1.6 and 1.2 t ha^{-1}, respectively. The boro rice grown in the dry season with MVs yielded almost 2.8 times that of the broadcast aman, but its cultivation was limited to areas with access to irrigation. With the rapid expansion of irrigation facilities, mainly through private-sector irrigation with power pumps and shallow tubewells, farmers' land-use option shifted from the low-yielding mixed aus-aman crop to boro rice. Consequently, the area under boro rice increased to 52% of the cultivated land by 1999-2000. With the expansion of area under boro rice, the area allocated to most of the other dry-season crops, particularly the pulses and oilseeds, declined substantially in the flood-prone areas.

An important point to note is the drastic reduction in cropping intensity over the period, from 174% to 143% of the cultivated land. The explanation for this phenomenon can be seen in Table 4, which reports the findings of the survey on the changes in cropping pattern. A major cropping pattern in the ecosystem was the triple-cropped mixed aus-aman rice followed by a nonrice crop (pulses or oilseeds), or a double-cropped aus-aman rice system. These cropping patterns have almost disappeared in favor of the single-cropped boro rice, thereby reducing the cropping intensity substantially. In 1999-2000, nearly 46% of the cultivated area was under the single-cropped rice system compared with 32% in 1987-88. It appears that there is further potential for increasing the area under rice cultivation if scientists can develop

Table 4. Changes in cropping pattern (% of cultivated land).

Cropping pattern	1987-88	1999-2000
Aman-fallow	19.1	17.2
Aus-aman	14.5	3.2
Aus-aman-nonrice	13.9	1.1
Aman-nonrice	13.0	11.7
Boro-fallow	12.6	29.0
Aman-MV boro	7.7	18.5
Nonrice-fallow	4.8	10.0
Others	14.4	9.3

shorter-duration modern boro and transplanted aman varieties so that farmers can safely grow two rice crops and keep the land fallow during the months of heavy flooding (Dey et al 1995).

The increase in yields of rice varieties grown in different seasons has been rather modest. For pulses and oilseeds, the yield rate actually declined (Table 3), which partly explains the shift of land from these crops although their prices increased faster than those of other crops because of growing scarcity (see below). The most dramatic increase in yield has been for vegetables and transplanted aman rice, which have benefited from the availability of high-yielding varieties. But there are market limitations for the expansion of area under vegetables and technical limitations for the expansion of area under transplanted aman now grown in patches of medium-highland and highland with shallow flooding. The increase in yields in the traditional crops of aus and broadcast aman has been about 15% over the 12-year period, which is a reflection of higher fertilizer use and better crop management. For boro rice, the yield increase was about 19%, which may be due to the development of newer high-yielding varieties and/or improved crop management practices. The average rice yield has increased substantially, by 66% (4.3% per annum), because of the change in seasonal crop composition—from the low-yielding broadcast aus and aman to the high-yielding boro rice.

Profitability and income from rice farming

Technological changes that occurred in the cultivation of individual rice varieties can be seen in Table 5. The most significant change has been the introduction of mechanized land preparation using power tillers. In 1987-88, animal-drawn plows were used for land preparation for the entire land. In 1999-2000, almost 80% of the cost of draft power came from the rental charge for power tillers. Mechanization reduced the cost of draft power in absolute terms (by 7.5%) over this period. Mechanization also contributed to a reduction in labor use by 21% in the cultivation of boro rice and by 11% in deepwater aman. The reduction in labor use for rice as a whole has been relatively low because of the increase in the area under boro rice, which uses more labor than aus or aman rice.

Table 5. Changes in rice production technology, 1987-88 to 1999-2000.

Indicators	Aus TV		B. aman TV		Boro MV		Overall rice production	
	1987-88	1999-00	1987-88	1999-00	1987-88	1999-00	1987-88	1999-2000
Labor use (d ha^{-1})	158	126	134	119	204	161	155	141
Family labor	83	58	48	49	76	51	63	52
Hired labor	75	68	86	70	128	161	92	89
Fertilizer use (kg ha^{-1})	36	58	36	53	388	351	112	200
Pesticide use (Tk ha^{-1})	Nil	26	Nil	34	442	671	112	348
Cost of power (Tk ha^{-1})	2,100	1,018	1,458	1,598	1,924	1,750	1,724	1,612

Table 6. Changes in input-output prices, 1988-2000.

Item	1987-88	1999-2000	Annual rate of growth (%)
Paddy (Tk kg^{-1})	5.35	6.02	1.0
Wheat (Tk kg^{-1})	6.83	7.52	0.9
Jute (Tk kg^{-1})	6.68	8.33	3.2
Pulses (Tk kg^{-1})	7.15	13.81	5.6
Oilseeds (Tk kg^{-1})	10.50	13.89	2.4
Potato (Tk kg^{-1})	2.07	5.29	8.1
Fertilizer (Tk kg^{-1})	5.52	8.56	3.8
Irrigation (Tk ha^{-1})	6,311.00	6,362.00	0.0
Labor (Tk d^{-1})	28.50	55.00	5.6
CPI[a] (1985-86 = 100)	129.00	238.00	5.3

[a] CPI = consumer price index.

Farmers used large amounts of fertilizer (351 kg of materials per ha in 1999-2000) in boro rice, but used substantially less in aus and aman rice. The use of fertilizer declined in boro by nearly 10% over the period, reflecting a more judicious use of chemical inputs. Total fertilizer consumption has increased by nearly 80%, however, over the 12-year period (5.0% per annum) because of the increased allocation of land to the high-fertilizer-using boro crop. The use of pesticides also increased faster because of the increased use in the boro crop and the large increase in the area under boro rice. Farmers used small amounts of pesticide in the aus and aman rice crops.

An important factor that would affect the profitability of farming is the changes in input-output prices over which farmers have little control. If input prices increase faster than output prices, profitability and farmers' income will decline even if yield increases (Table 6). Indeed, paddy prices increased much more slowly than other crops' prices and the prices of major inputs such as fertilizer and labor. The paddy price increased by only 1% per year vis-à-vis the 5.3% increase in the consumer price index (CPI) for rural areas and a 5.6% annual increase in the wage rate and 3.8% increase in the price of fertilizer. The movement in terms of trade thus has a depressing effect on profitability in rice farming vis-à-vis that of other crops.

Table 7. Changes in costs and returns in rice cultivation, 1988-2000.

Items	Aus TV		B. aman TV		Boro MV		Rice	
	1987-88	1999-2000	1987-88	1999-2000	1987-88	1999-2000	1987-88	1999-2000
Gross revenue (Tk ha^{-1})	7,434	9,885	9,797	12,765	25,011	34,714	12,582	23,574
Material inputs (Tk ha^{-1})	978	1,535	1,006	1,203	9,815	11,318	2,931	6,095
Cash cost (Tk ha^{-1})	3,393	5,763	3,691	6,216	13,921	19,023	5,816	12,309
Total cost (Tk ha^{-1})	7,582	8,928	6,343	9,035	17,585	21,958	9,086	15,303
Family income (Tk ha^{-1})	4,041	4,122	6,106	6,549	11,090	15,691	6,766	11,276
Operating surplus (Tk ha^{-1})	–148	927	3,454	3,730	7,426	12,756	3,496	8,271
Value added (Tk ha^{-1})	6,456	8,350	8,731	11,562	15,196	23,369	9,651	17,479
Yield rate (kg ha^{-1})	1,354	1,547	1,568	1,998	4,923	5,844	2,256	3,898
Unit cost (Tk kg^{-1})	5.60	5.77	4.05	4.52	3.57	3.76	4.03	3.92
Price (Tk kg^{-1})	5.49	6.39	5.57	6.39	5.08	5.94	5.35	6.00
Profit rate (%)	–2.00	10.70	37.50	41.40	42.3	58.00	32.80	54.01
Labor productivity (Tk d^{-1})	27.50	58.20	54.30	83.70	65.1	83.50	–	–

The rapid increase in wage rates compared with paddy prices, however, means a greater entitlement of staple food for the land-poor households that are dependent on manual labor for their livelihood. In 1987-88 with their daily wage, laborers could purchase 5.3 kg of paddy, which increased to 9.1 kg in 1999-2000, an increase of 4.6% per year.

The changes in the different indicators of the cost of and returns from rice cultivation are shown in Table 7. The cash cost of cultivation is nearly five times higher in the cultivation of boro rice than in the traditional aus or deepwater aman, indicating a heavy requirement of working capital for the shift in the cropping system. The investment is worth it, however, as the shift provided about 72% higher family income. The net income and operating surplus increased over time in nominal terms for the specific rice varieties, but at a slower rate than inflation, indicating a decline in real income.

However, because of technological progress and the increase in area under boro rice, the unit cost of cultivation has declined from Tk 4.03 to 3.92 per kg of paddy, while the price of paddy has increased by 13% over this period. The reduction in unit cost has enabled farmers to increase the rate of profits in paddy cultivation from 39% to 54% in spite of the slow increase in paddy prices. Labor productivity almost doubled during this period.

In spite of the increase in yield and the productivity of inputs, rice cultivation contributes very little to household sustenance. The family income from rice cultivation in 1999-2000 was only Tk 9,173 per farm household, or about Tk 1,521 (US$ 30) per capita, which is a small fraction of the household income (see below).

Table 8. Changes in the cost of rice production, 1987-88 to 1999-2000.

Cost items	Cost (Tk ha^{-1})		Share of item in total cost (%)	
	1987-88	1999-2000	1987-88	1999-2000
Seed	805	904	8.9	5.9
Fertilizer	509	1,706	5.6	11.1
Manure	145	59	1.6	0.4
Pesticide	113	349	1.2	2.3
Irrigation charges	1,363	3,029	15.0	19.8
Power rental	1,724	1,612	19.0	10.5
Hired labor	2,630	4,792	28.9	31.3
Imputed cost of family labor	1,796	2,860	19.8	18.7
Total	9,085	15,311	100.0	100.0

Environmental concerns

Major environmental concerns in rice cultivation are (1) the heavy use of agrochemicals, which cause harm to human health and water quality, (2) the erosion of biodiversity because of the adoption of a few profitable modern varieties, and (3) the decline in soil fertility because of intensive monoculture of rice (Pingali et al 1997, Brush et al 1992, Bose et al 2000). Limited data available from the survey indicate that these are not yet major problems for the flood-prone ecosystem in Bangladesh.

Pesticide use is limited to the cultivation of the boro crop grown during the dry season. Pesticide is hardly used in the crops during the wet season. Therefore, concerns about contamination of surface water in flood-prone areas because of the runoff of pesticides, causing harm to fish production, may not be serious. The amount of pesticide used in boro rice is also small, although it is growing over time. The cost of pesticides was only 2.3% of the total cost of rice production in 1999-2000 (Table 8).

As noted earlier, chemical fertilizer is used a lot in the cultivation of boro rice, but, for aus rice and deepwater aman rice, the use is still very low. In fact, the amount of chemical fertilizer used per hectare in boro cultivation declined over the period. Fertilizer is also used in a balanced proportion. The average amount of fertilizer used was about 296 kg of materials (140 kg of nutrients), of which the NPK proportion was 63:28:9. The decline in the use of farmyard manure is a concern, however. The cost of manure as a proportion of the total cost of production declined from 1.6% in 1987-88 to 0.4% by 1999-2000.

It can be noted from the cropping pattern information provided earlier that the practice of intensive monoculture of rice is not yet widespread in the villages under study. Nearly 46% of the area was under the single-cropped rice-fallow system and only 18% of the area was under the double-cropped aman-MV boro system. In the dry season, nearly one-third of the cultivated land was used in 1999-2000 for growing nonrice crops.

Table 9. Changes in yield of irrigated MV boro rice.

Flooding depth of parcel	1987-88 (kg ha^{-1})	1999-2000 (kg ha^{-1})	Percent change
Not flooded	3,740	4,292	15
Up to 30 cm	4,093	5,139	26
30 cm to 1.0 m	4,694	5,432	16
Over 1.0 m	4,847	6,359	32
Total	4,613	5,696	23

Table 10. The diversity of rice cultivars and popular varieties grown by season, 1999-2000.

Season	No. of rice varieties grown	Three popular varieties	Percent of area under three popular varieties
Aus	17	Laxmi Lata, Boilan, Haitta	76
Aman	54	Joyna, Laxmi Lata, Sada Bowl	36
Boro	33	BR-14, BRRIdhan-29, BR-8	41

Any decline in soil fertility should be reflected in the decline in yield over time. To assess whether this phenomenon has been occurring in the flood-prone ecosystem, we estimated the yield rate of a specific variety (MV boro rice) by controlling land type (Table 9). Yield is higher on parcels with greater flooding depth because of the benefit of composted waste and siltation from regular flooding, but, for each land type, the average yield has increased over time.

Table 10 presents the information obtained from the survey on the diversity of rice cultivars. A large number of rice varieties are still grown both in the wet season, to which modern varieties have yet to spread, and in the boro season, in which most of the land was cropped with modern varieties. In the 16 villages under study, 33 varieties were grown in the boro season, of which the most popular ones were BR14, BRRIdhan-29, and BR8. These varieties accounted for only 41% of the total boro area. The concentration of land under a few varieties for boro rice is not substantially large compared with that in aman rice, for which 36% of the land was used to grow three popular traditional varieties, Jaina, Laxmi Lata, and Sada Bowl.

Changes in the livelihood system

Table 11 shows the changes in the livelihood system for the households. During 1987-88, nearly 61% of the earning members were dependent on agriculture as the principal occupation: 36% in farming activities for the household and 24% selling labor services on others' farms. Very few workers were engaged in fishing or livestock raising as the principal occupation. The dependence on agriculture for livelihood has declined substantially, however, over the period with the increasing importance of rural nonfarm activities. In 1998, about 52% of the earning members were engaged in nonagricultural activities—various salaried and personal services, petty trade,

Table 11. Distribution of working members by occupation (% of earning members).

Occupation	Primary occupation		Primary and secondary occupations	
	1988	2000	1988	2000
Agriculture	61.3	49.0	87.5	67.5
Cultivation	35.7	34.9	52.9	44.3
Agricultural labor	23.9	12.6	30.9	20.0
Other agriculture	1.7	1.5	3.7	3.2
Nonagriculture	38.7	51.0	51.6	63.1
Trade and business	10.5	14.4	16.0	18.2
Service	19.9	23.0	22.5	24.8
Other nonagriculture	8.3	13.6	13.1	20.1
Total	100.0	100.0	139.1	130.6

shopkeeping and business, and providing labor in agro-processing activities, transport operations, and road and house construction. The proportion of cultivators remained almost the same, but the proportion of agricultural wage laborers declined substantially from 24% in 1988 to 13% in 2000. It seems that the mobility in rural occupation has been most pronounced among land-poor groups who were initially employed as agricultural wage laborers, but who have been increasingly seeking employment in transport operations, rural construction activities, and, at the lower end (on the productivity scale), services and trading activities. The mobility of the labor force from agriculture to nonfarm activities was facilitated by the improvement in rural roads and human capital, and the technological progress in rice cultivation that created employment opportunities in trade and transport operations related to the marketing of agricultural inputs and disposal of marketable surplus.

As a result, agricultural labor is becoming scarce, thus inducing change in the labor mark+et from daily wage contracts to piece-rated contracts for conducting specific agricultural operations (transplanting, weeding, and harvesting), which has had a positive effect on daily wage earnings. The shortage of agri-wage laborers has been inducing mechanization in agricultural operations, family-labor-based farming, and the increased supply of land in the tenancy market, which were noted earlier.

Growth and composition of rural income

Table 12 reports the findings of the survey on household income and its composition. The average household income estimated from the survey was Tk 62,524 for the 1999-2000 crop year. With an average household size of 6.01 persons, the per capita income was estimated at Tk 10,403, or US$207 at the prevailing exchange rate. The per capita income was estimated at Tk 3,763 for 1987-88 at current prices or Tk 6,942 at constant 1999-2000 prices after adjusting for the 84.5% increase in the CPI over

Table 12. Changes in the structure of household income.

	1987-88			1999-2000		
Source of income	Percent of households earning by source	Average income (Tk)	Percent of Income source	Percent of households earning by source	Average income (Tk)	Percent of income source
Agriculture	79.1	12,708	56.0	97.1	18,638	29.8
Rice farming	50.4	4,076	18.0	61.4	4,866	7.8
Nonrice farming	41.6	2,334	10.3	67.0	4,729	7.6
Agricultural wage	34.6	3,613	15.9	25.4	1,986	3.2
Other agriculture	68.6	2,685	11.8	91.3	7,0570	11.3
Nonagriculture	53.4	9,981	44.0	78.8	43,886	70.2
Trade	14.5	2,597	11.5	32.4	15,018	24.0
Service	25.5	3,664	16.1	42.9	13,373	21.4
Nonagricultural labor	32.4	2,883	12.7	25.8	3,947	6.3
Remittance	4.3	837	3.7	23.6	11,549	18.5
Total	100.0	22,689	100.0	100.0	62,524	100.0
Household size		6.03			6.01	
Per capita income		3,763			10,403	

the period (Table 6). Based on these figures, we estimate the growth in per capita income at 3.4% per year over this period. The growth in income came almost exclusively from the growth in rural nonfarm activities.

Several aspects are noteworthy with respect to the structure of household income and its change over the period. First, land ownership was no longer the predominant source of household income in rural Bangladesh. This conclusion is supported by the fact that income originating from crop activities (rice and nonrice farming and agricultural wages) accounted for 44% of household income in 1987-88, but declined drastically to about 19% by 1999-2000. The income from this source is dependent on the ownership and operation of agricultural land. Second, trade and services accounted for 45% of household income in 1999-2000, a substantial increase from 28% in 1987-88. The most dramatic increase has been in the share of remittance income from relatives employed in cities and abroad. The number of households receiving remittances increased from 4.3% in 1987-88 to 24% by 1999-2000, and the share of remittances in total household income over this period increased from 3.7% to 18.5%. These numbers suggest that ownership of nonland physical assets and the accumulation of human capital have become important determinants of household income. Third, the role of the labor market in income production is no longer of high importance. Self-employment in manual labor-based activities (cottage industry, transport operations, and construction work) and the hiring of labor service in crop production activity accounted for only 10% of rural household income in 1999-2000, a substantial decline from 29% in 1987-88. The wage income produced from the operation of the agricultural labor market accounted for 16% of household income in 1987-88. It dropped drastically to only 3.2% by 1999-2000.

The income from rice farming is small and it is becoming a relatively unimportant source of livelihood. The share of rice in total household income declined from 18.0% to 7.8% over this period. The increase in the supply of rice faster than demand, however, was the major factor behind the slow increase in the price of paddy (unhusked rice) compared with the general price index (see Table 6). While the CPI increased by 85% during the period, the price of paddy increased by 13% and the wage rate for agricultural laborers increased by 93%. The availability of rice at affordable prices contributed substantially to the improvement in the living conditions of the rural and the urban poor, who spend a large proportion of their meager income on staple food from the market. In 1998, a landless labor household could buy 5.3 kg of paddy (3.5 kg of rice) with a day's wage earnings and about 9.1 kg of paddy could be bought with the day's wage in 2000. The paddy-equivalent real wage increased by 71% during the period, a growth of 4.6% per year, faster than the growth in overall rural household income.

Changes in poverty

The measurement of poverty level involved (1) the specification of the income level below which a person is considered poor (the so-called "poverty line") and (2) construction of an index to measure the intensity and severity of poverty suffered by those whose income is below the poverty line. The most widely used measure of poverty in a population is the so-called "head-count" ratio, that is, the proportion of people living below the poverty line. Foster et al (1984) proposed a class of poverty measures that satisfy all the criteria for an ideal poverty measure (Sen 1981). Using this method, known as the FGT index, incidence, intensity, and severity of poverty were measured.

One needs to establish the poverty-line income to estimate poverty indices. Setting the poverty line has been a subject of great controversy in Bangladesh (Ravallion and Sen 1996). The popular approach used by poverty studies in Bangladesh is the cost-of-basic-needs method, which uses a normative consumable bundle of food items recommended for the average Bangladeshi population. It ensures a per capita daily intake of 2,112 calories and 58 grams of protein needed to maintain a healthy productive life. The required minimum expenditure on food items is estimated by using a set of prices for the reference year for the representative population group. An additional 40% allowance is then made for income needed to satisfy nonfood basic needs. Using this approach, Hossain et al (1997) estimated the poverty line at Tk 4,150 per person per annum for 1987-88. We estimated the poverty-line income at Tk 7,657 (US$152) for 1999-2000 by adjusting the 84.5% increase in the CPI for rural families over 1988-2000.

Table 13 reports the estimate of the percentage of households living below the poverty line using the above methodology. The head-count measure shows considerable improvement in the poverty situation during 1988-2000. The proportion of poor

Table 13. Changes in poverty situation, 1987-88 to 1999-2000.

Poverty indicators	1987-88	1999-2000	Percent reduction
Head-count index	64.8	53.9	17
Poverty-gap index	35.0	28.9	17
Squared poverty gap index	25.4	18.3	28

Table 14. Poverty situation for households classified by major source of income, 1999-2000.

Major source of income	Head-count index	Poverty-gap index	Squared poverty gap index
Services (27.8)[a]	27.6	11.9	6.1
Trade and business (15.1)	36.1	17.1	9.5
Farming (35.7)	69.0	38.8	26.9
Wage labor (21.6)	84.0	42.7	25.9

[a] Number in parentheses indicates the percentage of total households belonging to the category.

households was about 65% in 1987-88, which dropped to 54% by 1999-2000, a decline of about 17%. The most significant improvement occurred in the “squared poverty gap” index, which is a measure of the severity of poverty. The value of this index declined by about 28% during the period. This finding suggests an improvement in the economic conditions of the people even at the lower end of the poverty scale, particularly for the households that earn their livelihood from organizing small-scale informal activities in the nonfarm sector.

Table 14 presents the estimates of poverty for households classified by the major source of income for 1999-2000. As expected, the incidence of poverty was the highest (84%) for households whose major source of income was the selling of manual labor and the lowest (28%) for those whose major source of income was services. The incidence of poverty was very high (69%) for households dependent on farming. The severity of poverty was the same among farmers and day laborers. This finding supports the observation during field work that small and marginal farmers who are tied to tiny holdings are now economically worse off than landless wage laborers, who can take advantage of the relatively higher-paying productive jobs opening up in the rural nonfarm sectors because of the substantial improvement in the rural infrastructure in recent years. The landless also benefited from the rapid expansion of the microcredit program operated by nongovernmental organizations (NGOs).

The resurvey sought the opinion of the respondents regarding the economic standing of the households and the change in economic conditions during the 1990s. They were asked to categorize the relative economic standing of the households into one of four classes—rich, solvent, self-sufficient, and poor. Nearly 39% of the households considered themselves as poor, a much lower figure than the estimates obtained by the objective method using the survey data. Thirty-two percent of the households

Table 15. Changes in economic conditions (%) by major source of income.

Major source of income	Improved	Deteriorated	Net change
Services	60.0	22.2	37.8
Trade and business	57.6	28.8	28.8
Farming	48.9	31.9	16.6
Day labor	34.0	33.0	1.0
Total	48.5	29.9	19.0

considered themselves as self-sufficient (many households in this group will move in and out of poverty because of climatic vulnerability, price fluctuations, and health hazards, see Rahman and Hossain, 1995), 21% as solvent, and 9% as rich. Improvement in economic conditions was reported by 49% of the respondents and deterioration by 30%, indicating overall improvement in the well-being of the people during the 1990s. The improvement in livelihood was reported to be small for the households engaged in farming and it is much lower for the households that earned the major portion of their income from day labor (Table 15). Households dependent on services and trade and business reported a substantial improvement in their economic situation.

Summary and conclusions

Although the availability of land for agricultural production has been declining for rural households, the base of land productivity has increased because of the rapid expansion in the coverage of irrigation and the adoption of modern rice varieties during the dry season. In the wet season, farmers continue to grow traditional rice varieties because modern varieties are unsuitable for the flood-prone environment, but the area under these varieties has declined substantially over time, with farmers growing modern rice varieties during the dry season and leaving the land fallow during the wet season. Nearly 31% of the land was under the rice-fallow system in 1987-88, but this increased to 46% in 1999-2000. This led to a significant reduction in cropping intensity.

A major change in the livelihood system has been a reduction in the dependence of land-poor households on the agricultural labor market. The proportion of workers reporting agricultural wage employment as the principal occupation was almost halved from 1988 to 2000, as a result of increased employment opportunities available in the rural nonfarm sector. The higher incidence of tenancy and the introduction of mechanized land preparation using power tillers were two other significant changes during the period.

Although the increase in yield for individual crop varieties has been moderate, the overall increase in yield in rice cultivation has been substantial because of the reallocation of land from low-yielding aus and deepwater aman rice to high-yielding boro rice. The increase in productivity in rice cultivation, however, has not been translated into higher farm income because of the much slower increase in paddy prices compared with the wage rate and fertilizer prices. The nominal wage rate has increased almost on a par with the consumer price index, but, because of the slow increase in the nominal price of paddy, the entitlement of staple food for land-poor households has improved substantially.

Rice accounts for a small share of household income because of the very small farm size and rice's unfavorable terms of trade. Per capita income has grown at 3.4% per year, entirely because of a rapid expansion of income from nonagricultural sources—trade and business, transport operations, services, and remittances. This transformation from agriculture to a nonfarm-based rural economy has been facilitated by an improvement in human capital and the development of rural infrastructure, particularly rural roads. As a result of the rapid growth in the nonagricultural economy, there has been a moderate improvement in the poverty situation, although in absolute terms the level of poverty remains very high. The improvement has been more pronounced for households that derive income from services and trade as the major source, and only marginal for households engaged in farming or daily wage earning.

This study indicates that improvement in rice technology can make only a limited direct contribution to an increase in household income. The role of research for rice improvement should be seen as increasing rice supplies on a par with demand and reducing the unit cost of production so that the price of this dominant food staple could be kept within affordable limits for the rural and urban poor.

Since a large proportion of land in the flood-prone environment remains single-cropped, options to introduce a double-rice cropping system should be explored by developing shorter-duration and cold-tolerant aman and boro rice varieties. The incorporation of cold tolerance in modern boro varieties may allow the early havesting of boro and incorporation of traditional deepwater aman in the cropping system. Areas in which the floodwater recedes early may benefit from the availability of short-duration aman varieties that could be transplanted in late September and harvested in late December, still allowing time to grow boro rice during the dry season. Since farmers keep the seed from their own harvest for the large number of traditional aman varieties grown during the wet season, some yield gains could be made and biodiversity preserved from pure-line selections of the popular varieties and their distribution through the seed market.

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GIS-based natural resource analysis for rice production in the flood-prone areas of Bangladesh

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Rice production in flood-prone areas (except tidal flooding) has been explored taking into account specifically the natural resources—their problems and development opportunities. For this purpose, geographic information systems (GIS) have been used as a tool for resource analysis. Key resources such as land, soil, climate, and hydrology have been analyzed. Major parameters such as land type, permeability, available soil moisture, length of growing period (LGP), and thermal suitability were used in the process to delineate area, to map rice suitability and flood and drought hazards, and to demonstrate their effects on rice productivity in Bangladesh.

Bangladesh, with an area of 14.48 million ha, possesses a favorable terrestrial and hydrological environment and provides habitat for a large number of plants and animals. Land area is around 85% of the country and the total cropped area is 13.79 million ha (BBS 1998). Agriculture is the mainstay of the Bangladeshi economy and contributes more than 30% toward the country's gross domestic product (GDP). Bangladeshi agriculture is dominated by rice and approximately 74% of the cropped area is devoted to rice production. Rice is the major cash crop and the prime source of livelihood for the people of Bangladesh. Rice provides nearly 80% of the calorie needs of the average Bangladeshi.

A comparison of data from 1970 to 2000 shows that overall adoption of modern variety (MV) rice has increased sharply from only 4.64% in 1970-71 to nearly 62% in 1999-2000. This shift in rice cultivation practice and switchover from local varieties to MVs has dramatically increased the country's rice yield. The share of MVs was only 13.76% in 1970-71, but rose to nearly 77% in 1999-2000 (Mustafi and Azad 2000). Thus, the overall share of MV rice has increased nearly six times within the last 30 years, contributing 71% toward total rice production. The large-scale adoption of modern rice varieties has helped the country to achieve food self-sufficiency in cereal production in recent times. The Bangladesh Rice Research Institute (BRRI) has developed and released up to now 39 MVs of rice suitable for cultivation in different agroecosystems and crop seasons of the year.

Table 1. Rice area and production by season in Bangladesh (1995-98).

Area and production by season	1995-96			1996-97			1997-98		
	Local	HYV[a]	Total	Local	HYV	Total	Local	HYV	Total
Area (million ha)									
Rabi season (boro)	0.247	2.455	2.702	0.236	2.495	2.730	0.218	2.617	2.835
Kharif-I (aus)	1.123	0.416	1.539	1.116	0.474	1.590	1.075	0.488	1.563
Kharif-II (aman)[b]	3.378	2.269	5.647	3.331	2.471	5.803	3.261	2.547	5.809
Total area	4.748	5.140	9.888	4.683	5.440	10.123	4.555	5.651	10.206
Production (million t)									
Rabi season (boro)	0.369	6.739	7.188	0.354	6.985	7.340	0.341	7.659	8.001
Kharif-I (aus)	0.975	0.697	1.672	1.027	0.839	1.866	1.003	0.867	1.870
Kharif-II (aman)[b]	4.111	4.680	8.791	4.191	5.360	9.551	3.643	5.206	8.849
Total production	5.455	12.116	17.651	5.572	13.185	18.757	4.988	13.732	18.720

[a] HYV = high-yielding variety.
[b] Local includes traditional variety broadcast aman and transplanted aman.
Source: Statistical yearbook, BBS (1995-98).

Rice, the number-one food crop of Bangladesh, is grown extensively under a wide range of agroecological conditions. From flood-prone areas through terraces to hill valleys, farmers grow rice everywhere. But flood-prone areas (or floodplains, 80% of the country's area), including piedmont plains, are the major rice-growing areas of the country.

Seasonally, aus, aman, and boro rice are grown as the kharif-1 (end of March to mid-June), kharif-2 (mid-June to the end of October), and rabi (mid-November to mid-March) season, respectively. Out of the total rice production, on average, aman has the highest contribution (about 47%), followed by boro (about 43%) and aus (10%, Table 1). Aus and aman are grown by either broadcasting or transplanting. Normally, the MVs in both cases are grown by the transplanting method on higher sites of floodplain ridges while the tall local varieties are grown on lower sites of the ridges and in basin margins. Boro paddy, on the other hand, is grown both on ridges and in basins. Generally, the MVs of boro are preferred on floodplain ridges and in shallow basins, while the local varieties are confined to the basin depressions.

Nevertheless, rice production in the flood-prone areas of Bangladesh largely depends on the type of land and hydrological characteristics, including depth and duration of seasonal inundation of land, temporal and spatial variation of climatic behavior and its year-to-year variability, and the frequency of occurrence of natural hazards such as floods, drought, and pest and disease incidence. These factors determine the timeliness of sowing/transplanting of seeds/seedlings and thus their growth pattern and finally the safe and desired harvest of the crop. The depth of inundation, which actually figures into land type, is closely associated with the seasonal and varietal aspects of rice. The extent of inundation land type in Bangladesh appears in Table 2. Transplanted aus and aman, which usually include MVs, are grown on land above normal inundation to shallowly inundated (90-cm depth) land. Rainfed local varieties

Table 2. Extent of inundation land type.

Land type	Area (ha)	Inundation level during peak monsoon season	Proportion (%)
Highland	3,896,550	Land above normal inundation level	26.9
Medium highland (MHL)[a]	4,622,664	Land normally inundated up to about 90 cm	31.9
Medium lowland (MLL)	1,746,878	Land normally inundated up to 90–180 cm	12.0
Lowland	1,102,622	Land normally inundated up to 180–300 cm	7.7
Very lowland	193,243	Land normally inundated deeper than 300 cm	1.3
Total soil area	11,561,957		79.8
River, urban, homesteads, etc.	2,924,321		20.2
Total	14,486,278		100.0

[a] For some purposes, this is divided into MHL1 inundated up to 30 cm and MHL2 inundated up to 30–90 cm.
Source: AEZ/GIS database system of BARC.

of broadcast aus and aman, on the other hand, are usually grown on middle to lower sites with relatively deeper inundation (>90–180 cm and even more), while deepwater aman can survive beyond 300-cm inundation. The relationship between inundation depth and rice variety is examined in the following pages.

At this stage, let us point out that the term “flood-prone” will cover only those rice areas that are affected by seasonal flooding/submergence. Rice areas affected by tidal flooding have been excluded. So, our narration will cover shallow to deep flooding only.

Natural resource base

The natural environment of Bangladesh is diverse and complex. As such, both traditional and modern systems of land use are adopted and practiced with wide variation in management. This heterogeneity of agricultural practices has large implications for the production environment of crops and for the depletion of the natural resource base and vulnerability. The resource base broadly covers land/soil, climate, hydrology, labor, and capital. For our purpose of natural resource analysis, this will cover only the biophysical resources as related to agricultural cropping. This essentially involves four major components: landform, soil, hydrology, and climate. These components on interaction determine the prospects and problems related to optimization of crop production (rice in this particular case). A brief analysis of these natural resources, with emphasis on key elements, is provided in the following sections.

Landform

Landform covers land characteristics in terms of topographic position of land in relation to seasonal inundation. This is especially important for flood-prone areas of Bangladesh and it is a deciding factor for seasonal rice cultivation in the country. The flooding/inundation status will indicate whether the land is inundated or not, and, if it is inundated, to what depth. Further, when does the inundation start and end, and, in between, when does the inundation attain its peak? These are important determinants in selection and sowing/transplanting of appropriate rice varieties in different land types and in different seasons of the year. For future discussion, the agroecological zone (AEZ) map of the country is given in Figure 1, distribution of land type by AEZ appears in Table 3, and the inundation land-type map is provided in Figure 2.

Generally, transplanted rice is grown in areas with a shallower depth of inundation, whereas broadcast rice is preferably grown in areas with deeper inundation. Further, MVs are prevalent in the former areas and tall local varieties occupy the latter. Table 4 further clarifies this. The suitability of rice cultivation by land type is given in Figure 3 and the land suitability of rice in Bangladesh under rainfed and irrigated culture appears in Table 5.

Soils

Rice, a high-water-demanding wetland crop, grows well on soils with slow permeability/percolation, that is, on soils with high water retention capacity. In this respect, heavy loams and clayey soils, unless otherwise constrained (natural hazards, nutrient deficiency, very low or very high pH, etc.), are the most suitable soils for rice cultivation in the flood-prone areas of Bangladesh. The plowpan area of 2.82 million ha is good for transplanted rice but bad for others. Thus, soils of the major river floodplains and piedmont plains are the major rice-growing areas of the country. Figures 4 and 5 show a generalized drainage suitability and permeability map for T. aman and Figure 6 shows the available soil moisture. Drainage, permeability, and soil moisture have implications for the cultivation of wetland rice (transplanted aman, for example), while soil moisture has a great influence on dry-season rice and other rabi crops. Figure 7 shows the intensity of rabi-season irrigation.

Ridges of the river floodplains, old estuarine floodplain, major parts of the piedmont plains, and young estuarine floodplain (nonsaline) are generally shallowly inundated and have loamy soils with moderately slow permeability. Thus, they provide the highest opportunity to grow modern varieties of both transplanted aus and aman in the kharif-1 and kharif-2 seasons. The floodplain basins, on the other hand, are normally deeply flooded and allow broadcast aus and aman in the kharif season. They generally have slowly permeable clayey soils with which irrigation is used extensively for MV boro in the rabi season. Highlands with no flooding are risk-free lands, where MV boro is extensively cultivated under irrigation. Very deeply flooded or perpetually wet basin soils with heavy clays are usually used for local varieties of boro. Based on the factors discussed and maps provided earlier, the potential of T. aman area is delineated and mapped in Figure 8 (with support in Table 6).

Table 3. Distribution of land type by agroecological zones (AEZ).

AEZ name	Land type (area in ha)							Total
	Highland	Medium	Medium highland	Lowland lowland	Very lowland	Group total	Miscellaneous	
Old Himalayan Piedmont Plain	234,315	136,762	2,912	0	0	373,989	26,808	400,797
Active Tista Floodplain	1,968	59,750	0	0	0	61,718	21,926	83,644
Tista Meander Floodplain	329,759	483,709	40,358	5,131	0	858,957	87,847	946,804
Karatoya-Bengali Floodplain	59,940	113,382	34,903	11,509	1,447	221,181	35,977	257,158
Lower Atrai Basin	1,724	7,165	17,780	54,681	0	81,350	3,755	85,105
Lower Punarbhaba Floodplain	0	0	1,290	7,737	0	9,027	3,869	12,896
Active Brahmaputra-Jamuna Floodplain	16,924	117,287	63,324	26,155	0	223,690	95,311	319,001
Young Brahmaputra and Jamuna Floodplain	105,500	245,206	115,366	52,489	0	518,561	73,833	592,394
Old Brahmaputra Floodplain	201,501	251,781	143,971	53,666	91	651,010	72,027	723,037
Active Ganges Floodplain	39,183	109,467	61,064	14,036	0	223,750	109,697	333,447
High Ganges River Floodplain	562,642	416,688	161,146	30,573	0	1,171,049	149,499	1,320,548
Low Ganges River Floodplain	101,636	231,316	247,194	109,232	14,169	703,547	93,204	796,751
Ganges Tidal Floodplain	38,190	903,068	16,269	68	0	957,595	748,978	1,706,573
Gopalganj-Khulna Beel	6,353	29,208	90,912	63,772	25,461	215,706	8,994	224,700
Arial Beel	0	0	1,877	10,538	0	12,415	2,021	14,436
Middle Meghna River Floodplain	13	12,755	43,599	39,790	17,520	113,677	41,787	155,464
Lower Meghna River Floodplain	12,294	25,031	29,210	72	0	66,607	24,327	90,934
Young Meghna Estuarine Floodplain	734	418,297	68,230	0	0	487,261	439,624	926,885
Old Meghna Estuarine Floodplain	13,932	183,945	253,691	166,089	23,563	641,220	132,806	774,026
Eastern Surma-Kusiyara	22,273	116,099	90,594	169,405	158	398,529	63,630	462,159
Sylhet Basin	338	15,799	88,333	197,827	106,907	409,204	48,141	457,345
Northern and Eastern Piedmont Plain	132,479	126,688	64,628	36,722	3,499	364,016	39,742	403,758
Chittagong Coastal Plain	61,835	163,512	47,671	116	0	273,134	98,882	372,016
St. Martins' Coral Island	264	508	16	0	0	788	16	804
Level Barind Tract	149,590	276,239	21,744	10,179	0	457,752	47,099	504,851
High Barind Tract	148,939	1,152	109	655	0	150,855	9,109	159,964
North-Eastern Barind Tract	38,922	60,766	719	0	0	100,407	7,519	107,926
Madhupur Tract	233,945	76,416	31,568	39,583	0	381,512	42,847	424,359
Northern and Eastern Hills	1,375,100	39,396	7,255	905	140	1,422,796	394,376	1,817,172
Akhura Terrace	6,257	1,272	1,145	1,692	288	10,654	670	11,324
Country total	3,896,550	4,622,664	1,746,878	1,102,622	193,243	11,561,957	2,924,321	14,486,278

Source: AEZ/GIS database system of BARC.

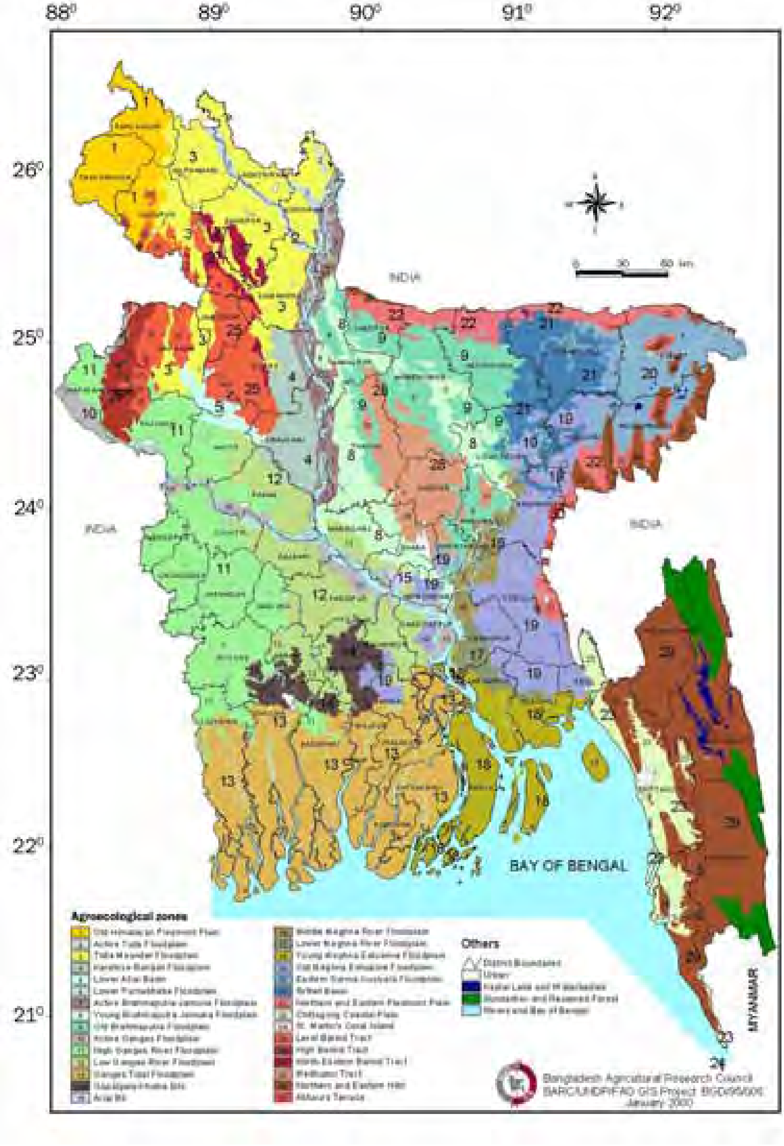


Fig. 1. Agroecological zones in Bangladesh.

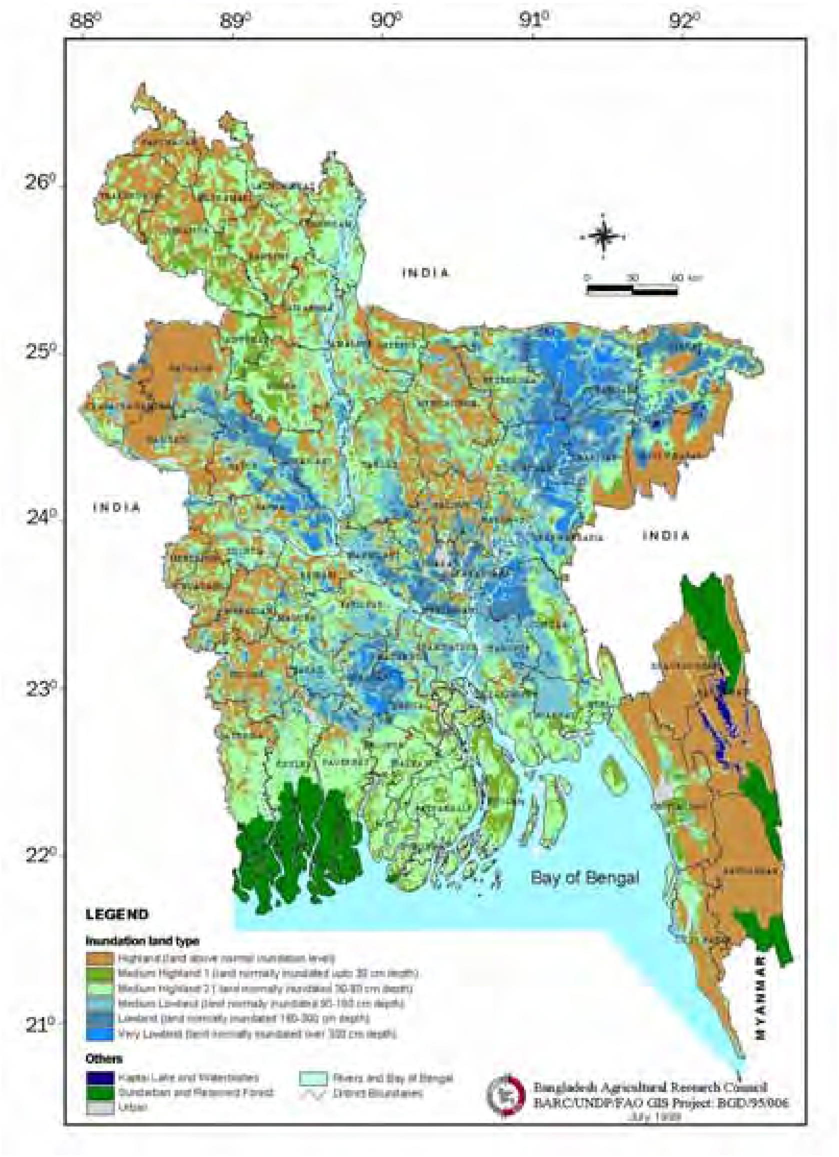


Fig. 2. Inundation land types in Bangladesh.

Table 4. Rice cultivation by land type.

Type of rice	Inundation land type
Transplanted aus (MV)	Highland, medium highland-1, medium highland-2 mostly, and to some extent on medium lowland
Transplanted aman (MV)	Mostly on medium highland-1 and highland with clayey soils, also on medium highland-2, but not on land inundated deeper than 90 cm
Deepwater transplanted aman (DTW)	Medium lowland mostly, to some extent lowland and very lowland with risk
Broadcast aus (LV)	Mostly on medium lowland (90–180 cm) and to some extent on lowland (180–300 cm)
Broadcast aman (LV)	Both medium lowland and lowland and to some extent very lowland (>300 cm)
Boro (MV)	With irrigation, on all land types except very lowland
Boro (LV)	Especially on very lowland without irrigation

Source: AEZ/GIS database system of BARC.

Hydrology

Hydrology covers both normal inundation from monsoon rain (*barsa*) and disastrous inundation caused by flood *(banna)*. In crop agriculture, inundation determines cropping environment and land type.

Seasonal inundation occurs because of the individual or combined effect of rainfall, riverbank erosion, flash flood, or localized stagnation of water. When the situation goes beyond the level of tolerance in terms of extent and severity of flooding, flood occurs. Flood may be categorized into riverine and flash flood. In the first case, the river level rises, overflows the riverbank, and engulfs vast areas of agricultural land, households, and infrastructure. In the second case, heavy runoff from the hills (flash flood) occurs because of torrential rainfall and often submerges large areas in the lower ridges, causing severe damage to agricultural crops, especially aus and transplanted aman paddy at different stages of growth. In the depressed basin (*haor*) areas, local boro is thus preferred and well suited to avoiding flash flood.

Flash flood occurs almost every year and sometimes more than once in the same year. The dimension of affected area and the intensity of damage caused are by far less than with river flood. Considering all related factors, flood-prone areas of Bangladesh have been categorized and shown in Figure 9. To demonstrate the influence of early and late flooding, two more maps are provided (Figs. 10 and 11). All flooding has serious implications for rice cropping, varietal selection, and the crop harvest.

Climate

Rainfall and temperature provide the primary layers of climatic information. Total annual rainfall in Bangladesh is one of the highest in the world (1,400 to >5,000 mm). Unfortunately, most of this rainfall is ineffective for rainfed agriculture because of its

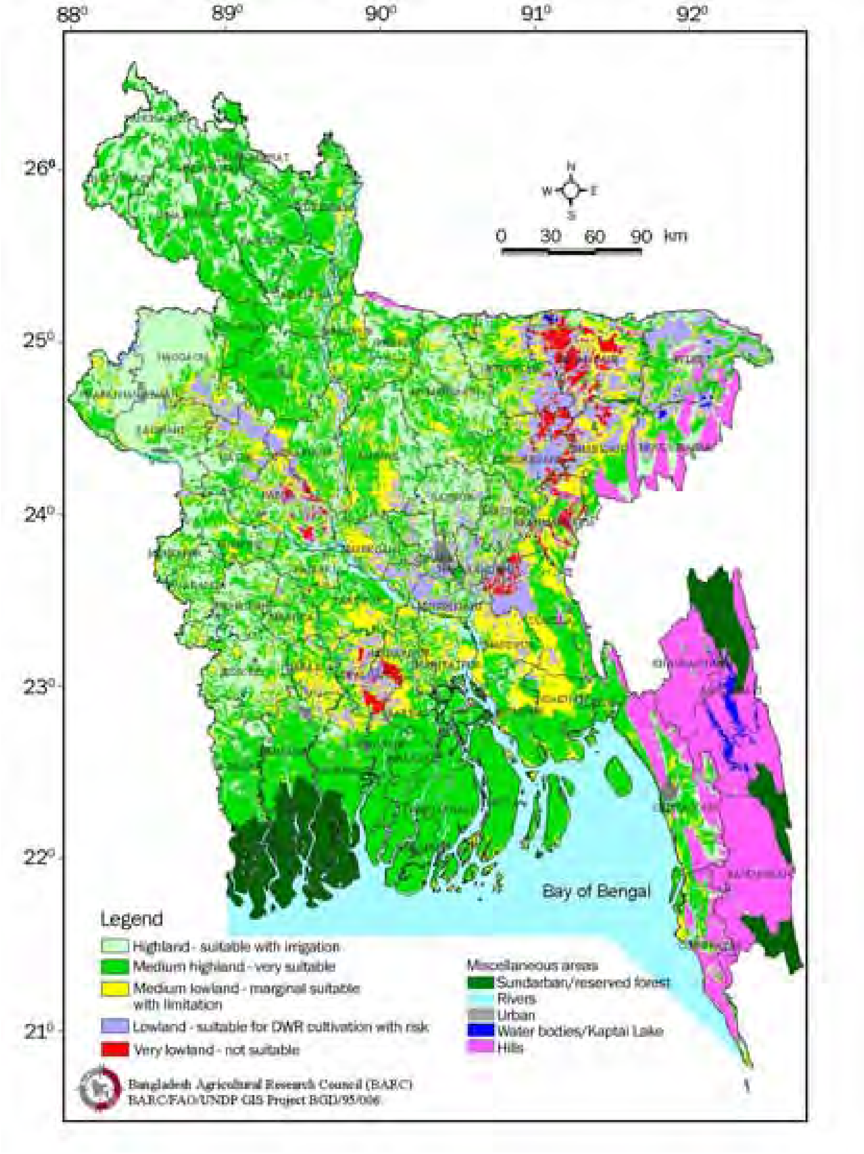


Fig. 3. Sustainability of rice cultivation by land type in Bangladesh.

Table 5. Land suitability of rice under rainfed and irrigated ecosystem in Bangladesh (in ha).

Crop	Rainfed					Irrigated				
	VS[a]	S	MS	LS	NS	VS	S	MS	LS	NS
HYV boro (quick maturing)	0	0	0	0	11,466,913	823,412	3,849,133	2,696,525	2,491,225	1,606,618
HYV boro (late maturing)	0	0	0	0	11,466,913	43,114	1,460,626	1,776,321	4,625,929	3,560,923
Local boro	0	0	0	0	11,466,913	2,708,747	3,719,174	1,917,909	1,714,262	1,406,821
HYV T. aus	0	852,942	1,680,842	3,826,838	5,106,291	1,221,757	591,672	3,308,637	1,747,818	4,597,029
Broadcast aus	0	1,023,622	2,080,587	3,502,011	4,860,693	0	1,867,742	2,963,931	2,427,442	4,207,798
Local T. aus	0	1,511,013	3,464,597	2,056,497	4,434,806	2,480,199	2,486,073	1,815,852	306,396	4,378,393
HYV T. aman	0	1,874,419	1,085,220	3,718,011	4,789,263	1,384,921	991,364	2,751,779	1,776,517	4,562,332
HYV T. aman after HYV/local T. aus	0	0	298,020	854,387	10,314,506	0	849,584	1,258,415	4,172,954	5,185,960
Local T. aman after HYV/local T. aus	0	34,705	648,143	4,764,562	6,019,503	0	2,304,921	2,696,875	2,046,327	4,418,790
Local T. aman	0	2,665,991	3,244,978	1,159,599	4,396,345	2,301,487	2,648,488	1,832,149	306,396	4,378,393
Deepwater aman	0	1,500,463	2,131,623	4,495,155	3,339,672	0	2,013,307	3,431,597	3,790,761	2,231,248

[a] VS = very suitable (80% or more of maximum attainable yield, MAT), S = suitable (60–80% of MAT), MS = moderately suitable (40–60% of MAT), LS = marginally suitable (20–40% of MAT), and NS = not suitable (< 20% of MAT); HYV = high-yielding variety.
Source: AEZ/GIS database system of BARC.

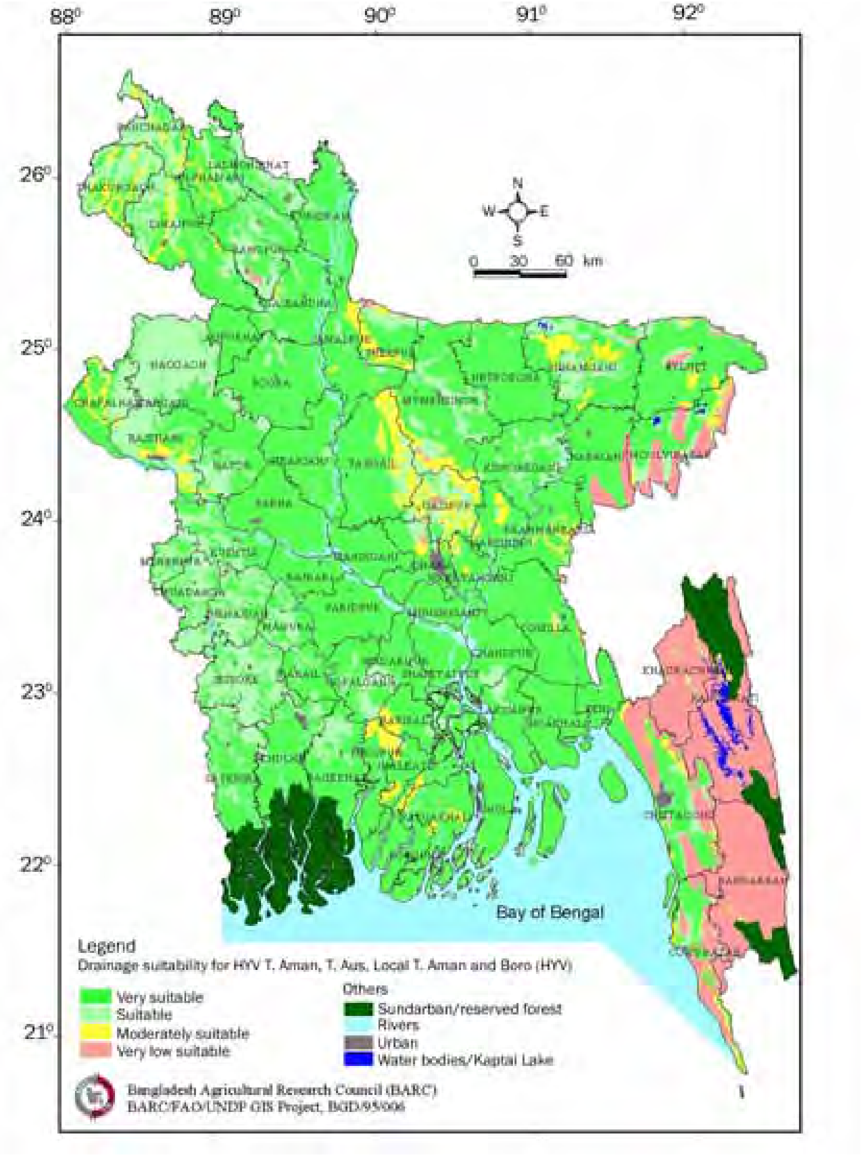


Fig. 4. Drainage suitability for rice cultivation in Bangladesh.

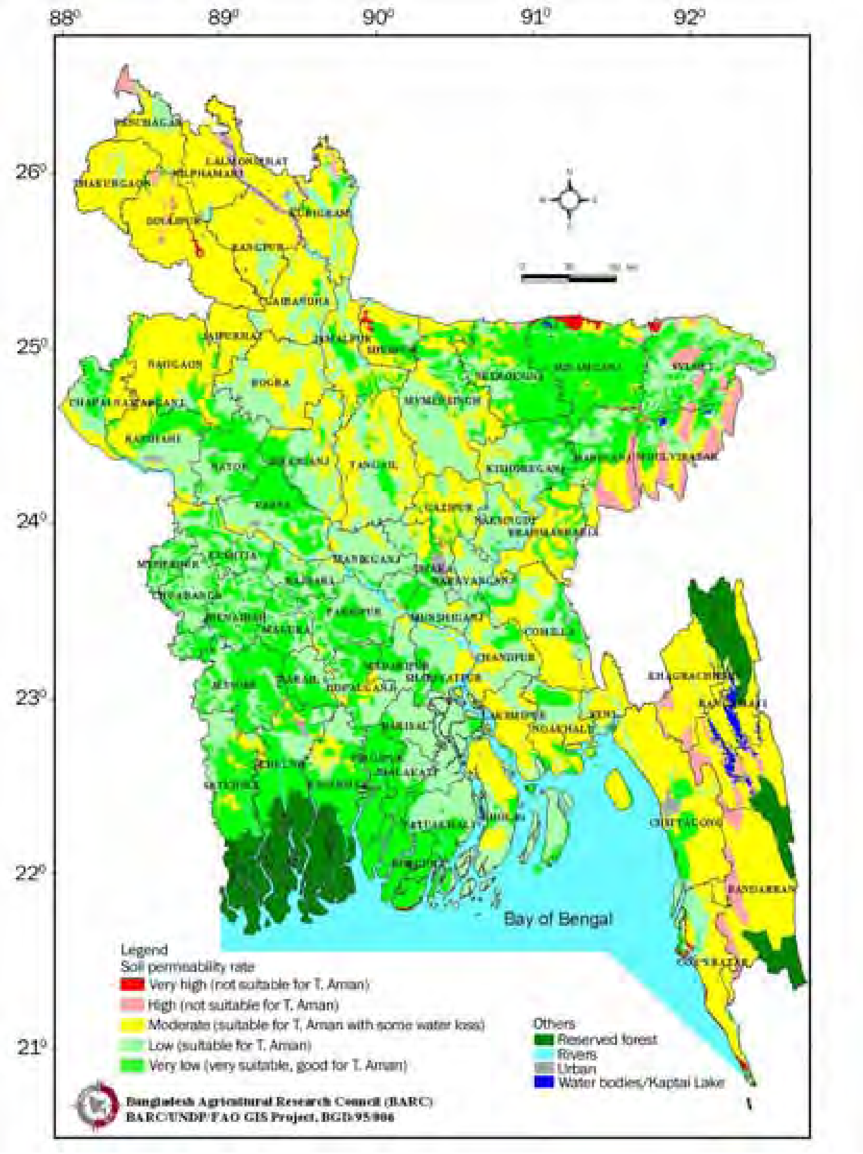


Fig. 5. Suitability of T. aman by soil permeability in Bangladesh.

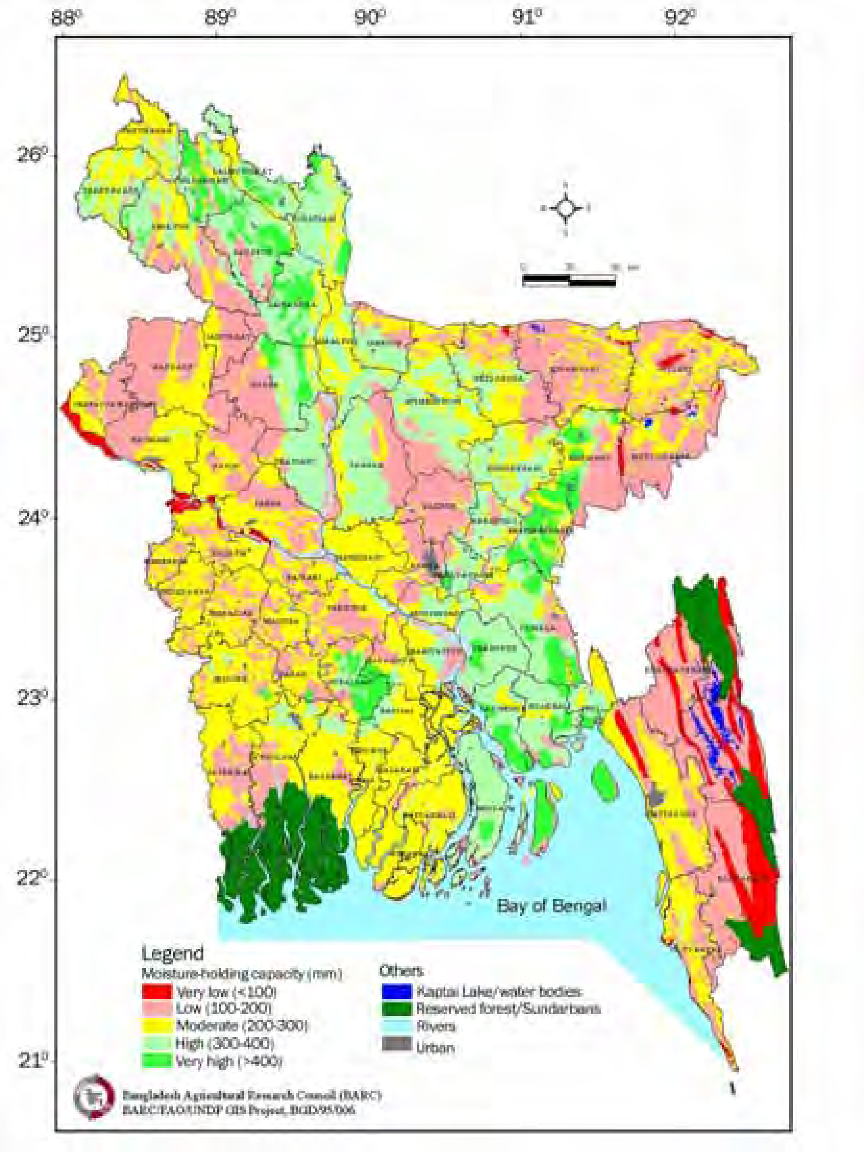
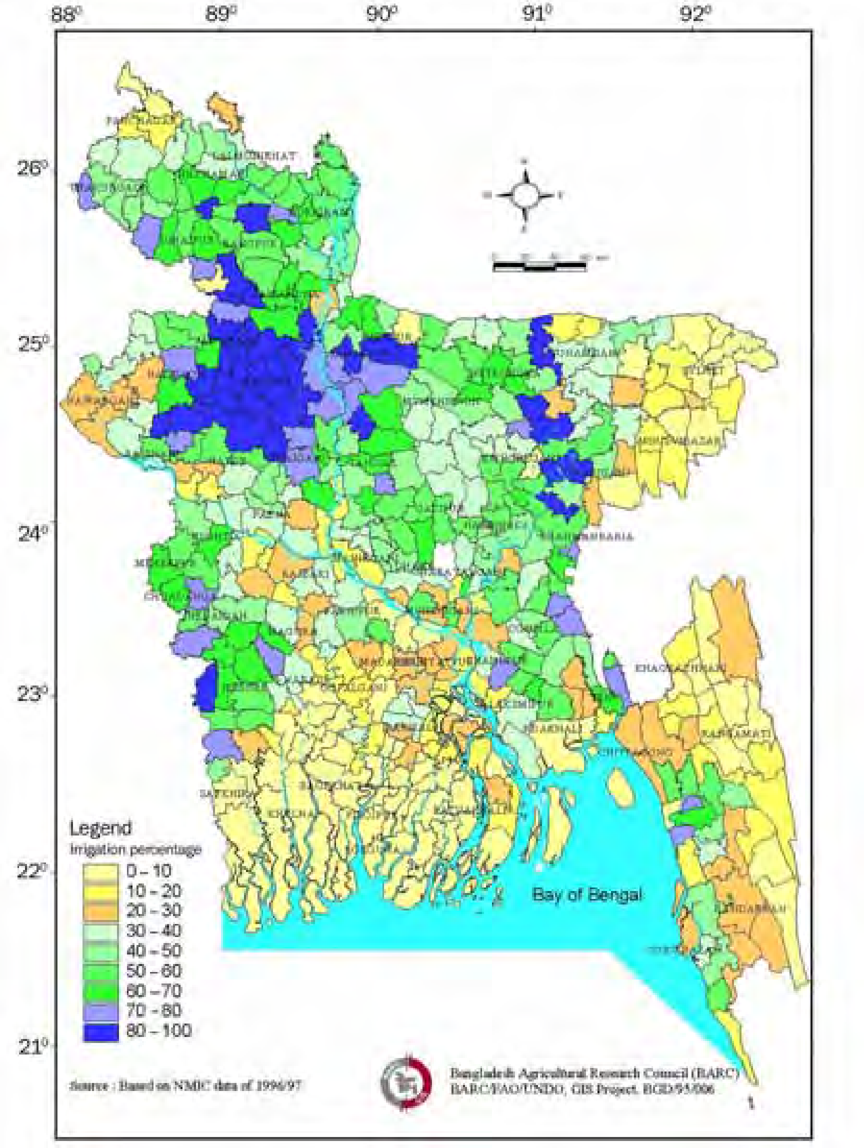


Fig. 6. Available soil moisture in Bangladesh.



Source : Based on NMIC data of 1996/97

Bangladesh Agricultural Research Council (BARC)
BARC/FAO/UNDO, GIS Project, BGD/95/006

Fig. 7. Intensity of rabi season irrigation in Bangladesh.

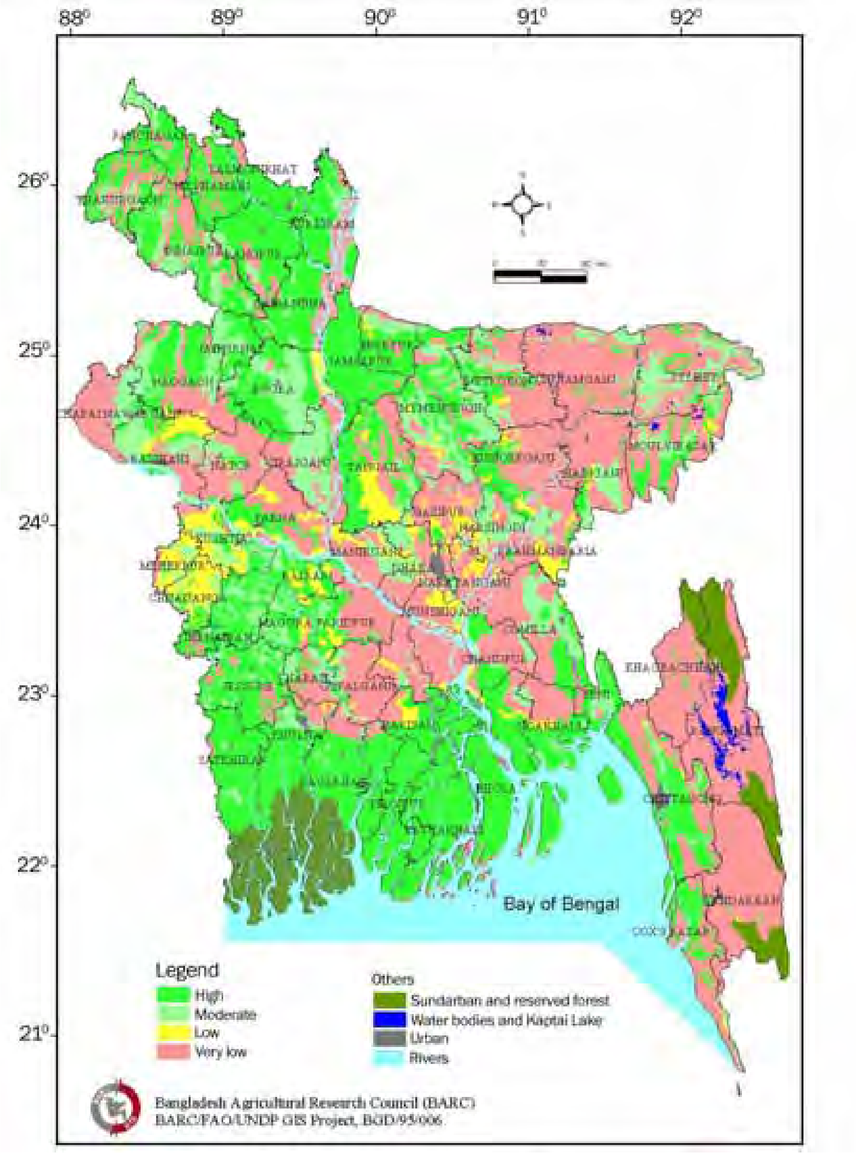


Fig. 8. Potential of T. aman in Bangladesh.

Table 6. Potential of T. aman[a] and suitability of areas by some key parameters (in ha).

Suitability class	T. aman potential	Moisture-holding capacity	Land type	Permeability	Drainage
Very suitable	4,929,380	647,223	4,622,664	2,993,004	7,492,193
Suitable	–	2,333,560	3,896,550	3,443,867	2,151,091
Moderate	2,057,836	4,250,286	1,746,878	4,682,573	593,648
Low	663,159	3,902,929	1,102,622	387,686	1,325,025
Very low	3,911,582	427,959	193,243	54,827	–
Other	2,924,321	2,924,321	2,924,321	2,924,321	2,924,321
Total	14,486,278	14,486,278	14,486,278	14,486,278	14,486,278

[a] T. aman potential is derived through GIS-based resource analysis.
Source: AEZ/GIS database system of BARC.

Moisture-holding capacity
Very suitable = > 400 mm
Suitable = 300–400 mm
Moderate = 200–300 mm
Low = 100–200 mm
Very low = < 100 mm
Land type
Very suitable = medium highland
Suitable = highland
Moderate = medium lowland
Low = lowland
Very low = very lowland

Permeability
Very suitable = very low permeability (clay and silty clay soil)
Suitable = low permeability (silt and silty clay loam soil)
Moderate = medium permeability (loam and silt loam soil)
Low = high permeability (loamy sand and sandy loam soil)
Very low = very high permeability (sand)

Drainage (subsurface)
Very suitable = poorly drained soil
Suitable = imperfectly drained soil
Moderate = moderately well- and very poorly drained soil
Low = well-drained soil

uneven distribution pattern; 80–90% of the total rainfall occurs within four months from June to September. December to mid-March is almost rainless. During that time, boro cropping is done on the basis of irrigation (except depressed basins). For rice cropping, it is not the total annual rainfall but its distribution pattern over the year with a sustained residual moisture supply for growing rice that counts most. The onset of rainfall and its termination are another important factor that determines the length of the growing period (LGP), that is, the time available for growing rice and its start and end period. This, for selected locations, is furnished in Table 7. To elaborate further, reference kharif and rabi LGPs are provided in Figures 12 and 13.

The thermal regimes including hot summer (40 °C or more) and cool winter (<15 °C) temperatures are the other components of climate that determine rice cropping and cultivar. The hot summer temperature influences kharif crop performance. The occasional rise in temperature surpassing 40 °C in April-May, high evapotranspiration, and lowering of the groundwater table and its persistence for a few days cause severe damage to kharif crops such as aus and broadcast aman. Dry spells also affect T. aman, necessitating supplementary irrigation for sustained growth of the crop. In this regard, drought-affected areas in different seasons of the year are given in Table 8 and, as an example, the effect of drought on T. aman is shown in Figure 14. The prevalence of cool winter temperature (<15 °C) in December and January also affects already transplanted boro paddy at the tender stage or forces a delay in trans-

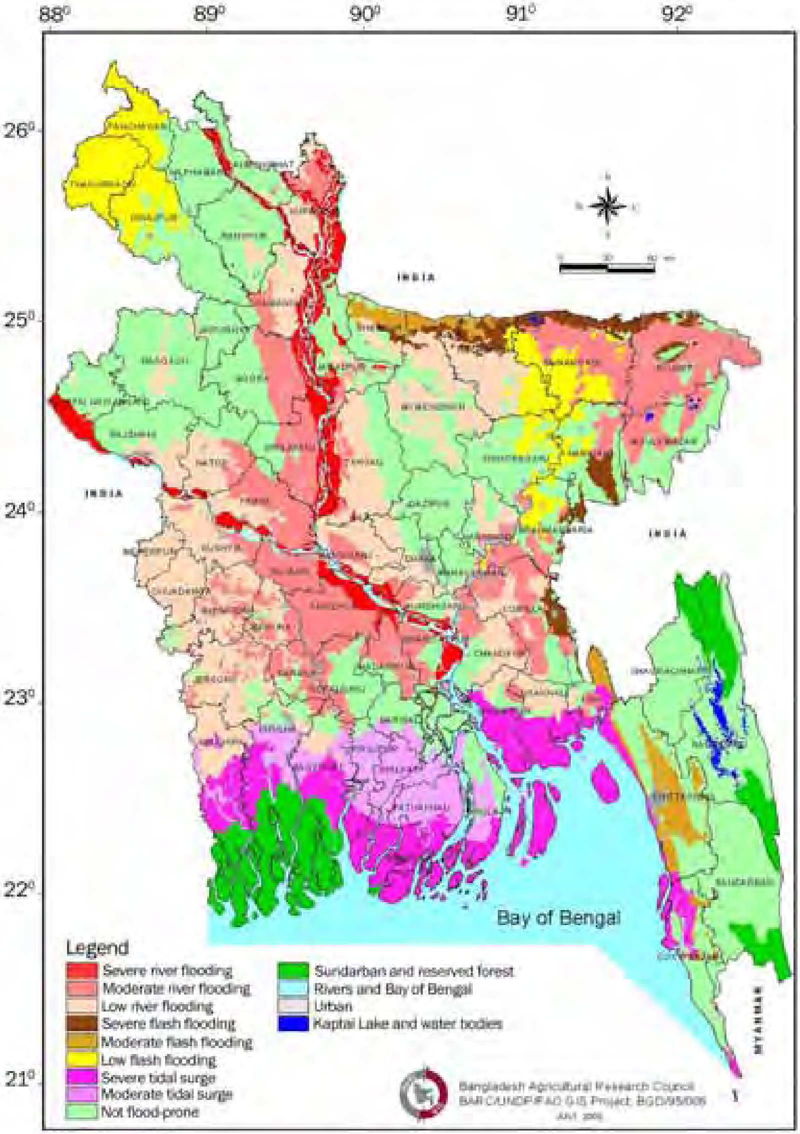
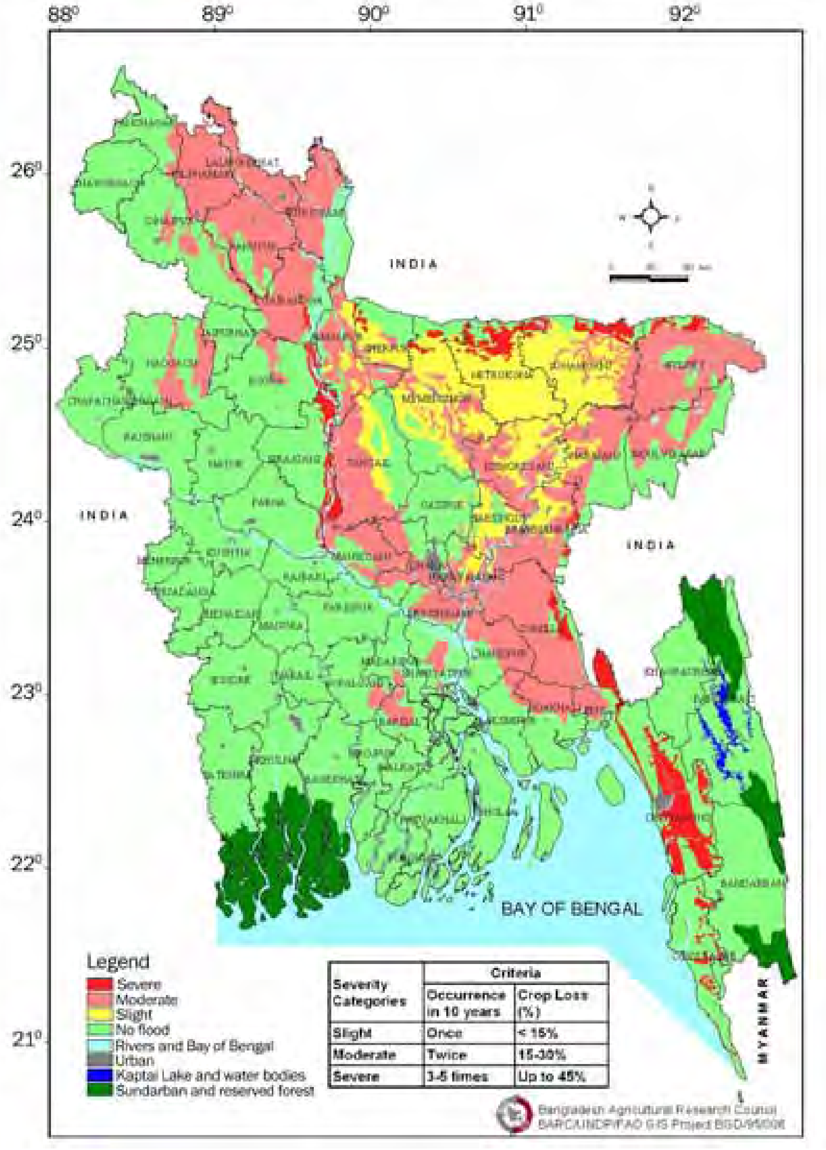


Fig. 9. Flood-prone areas in Bangladesh.



Severity Categories	Criteria	
	Occurrence in 10 years	Crop Loss (%)
Slight	Once	< 15%
Moderate	Twice	15-30%
Severe	3-5 times	Up to 45%

Fig. 10. Early monsoon flood in Bangladesh.

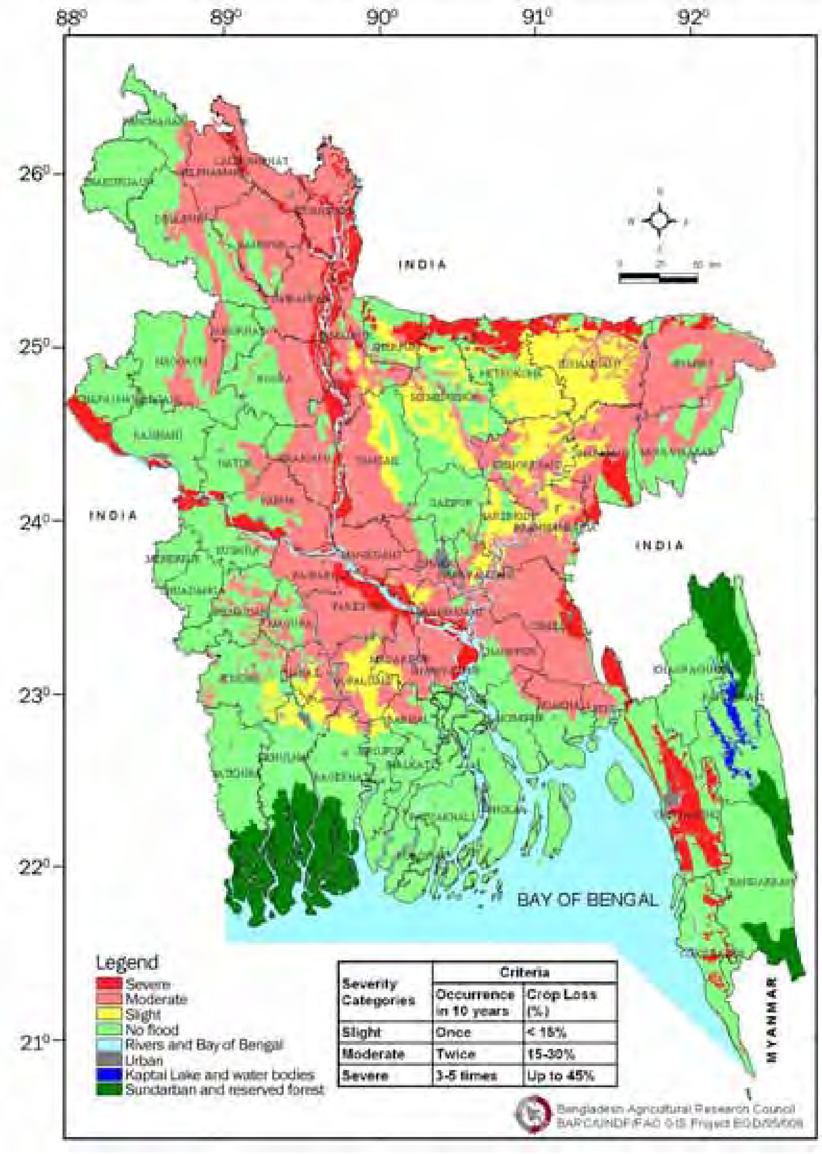


Fig. 11. Late monsoon flood in Bangladesh.

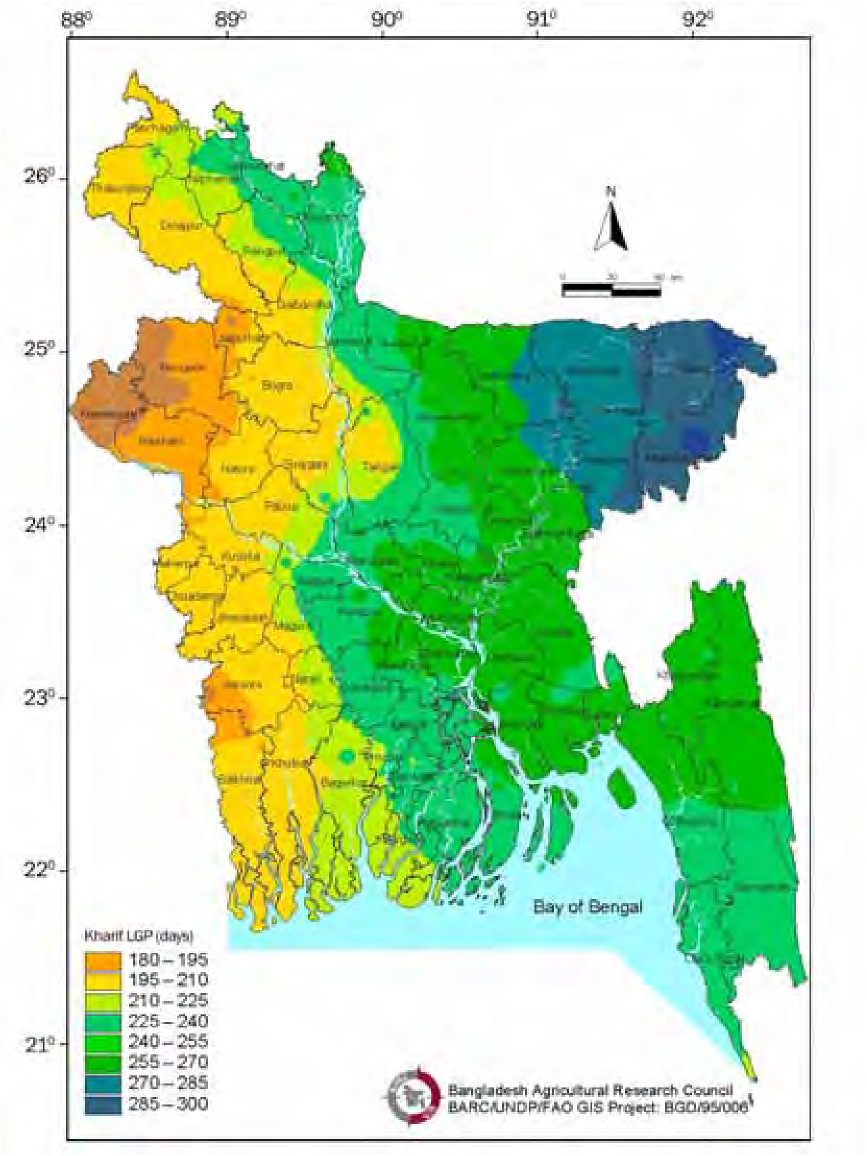


Fig. 12. Reference for kharif length of growing period in Bangladesh.

Table 7. Start, end, and duration of different growing seasons at selected locations of Bangladesh.

Location	Start of K1[a]	End of K1	Duration (d)	Start of K2	End of K2	Duration (d)	Start of rabi	End of rabi	Rabi duration (d)
Kushtia	1 May	24 May	24	24 May	3 Oct	127	3 Oct	6 Feb	115
Chuadanga	3 May	21 May	19	21 May	9 Oct	136	9 Oct	3 Feb	115
Rangpur	15 Apr	3 May	18	3 May	18 Oct	160	18 Oct	1 Mar	117
Rajshahi	27 Apr	15 May	15	15 May	15 Oct	139	15 Oct	1 Feb	100
Bogra	24 Apr	9 May	18	9 May	12 Oct	147	12 Oct	1 Feb	111
Mymensingh	12 Apr	27 Apr	18	27 Apr	24 Oct	176	24 Oct	1 Mar	114
Sylhet	9 Mar	24 Mar	15	24 Mar	27 Oct	216	27 Oct	1 Feb	124
Ishurdi	18 Apr	9 May	24	9 May	15 Oct	130	15 Oct	1 Feb	115
Dhaka	3 Apr	21 Apr	21	21 Apr	21 Oct	180	21 Oct	1 Feb	115
Comilla	3 Apr	18 Apr	18	18 Apr	18 Oct	173	18 Oct	1 Feb	112
Jessore	29 Apr	18 May	18	18 May	18 Oct	136	18 Oct	1 Feb	112
Khulna	16 Apr	3 May	18	3 May	21 Oct	160	21 Oct	1 Feb	112
Barisal	16 Apr	1 May	18	1 May	24 Oct	165	24 Oct	1 Mar	95
Chittagong	1 Apr	21 Apr	18	21 Apr	31 Oct	174	31 Oct	1 Feb	95
Cox's Bazar	18 Apr	3 May	15	3 May	24 Oct	182	24 Oct	1 Feb	88

[a] K1 = kharif-1 season (prekharif), K2 = kharif-2 season, and rabi = dry season.
Source: AEZ/GIS database system of BARC.

Table 8. Extent of drought severity in Bangladesh by crop season (in million ha).

Drought class	Kharif-2/T. aman	Rabi	Prekharif
Very severe	0.34	0.45	0.40
Severe	0.74	1.71	1.15
Moderate	3.17	2.95	4.76
Slight	2.90	4.21	4.09
No drought	0.68	3.17	2.09
Non-T. aman	4.71	–	–

Source: AEZ/GIS database system of BARC.

planting to overcome cold exposure of the young seedlings. Figure 15 shows the area and extent of that phenomenon that influences rice production.

Constraints to rice cropping

Generally speaking, the flood-prone areas of the country are constrained by either soil or environment-related problems such as the frequent occurrence of hazardous flood, drought, drainage congestion, nutrient deficiency, lack of moisture, river-bank erosion, etc. Specific to rice cropping, poor physical and chemical properties, low

Table 9. Problems related to rice production in the flood-prone areas of Bangladesh.

Nature of problem[a]	Area (million ha)
Organic-matter-deficient soils	7.55
Sulfur-deficient soils	3.95
Peat/muck	0.13
Zinc-deficient soils	1.74
Very coarse-textured soils	0.44
Soils with very firm plowpan	2.82
Soils with very low available moisture-holding capacity	5.73
River bank erosion/burial by raw sandy alluvium	1.20
Waterlogging	0.70

[a] Estimates are based on available information. Sum of the problem areas is more than the total arable area of the country. This is because, in most cases, the same area appeared under more than one type of problem.

organic matter content, tillage problems, low load-bearing capacity (peat, muck), and pest and disease incidence are the major problems hindering production. Table 9 shows a country scenario of rice production-related problems.

GIS as a tool for sustainable rice cropping

The major advantage of geographic information systems (GIS) technology is its capacity to handle a large volume of both spatial and temporal data along with related attributes and at the end to produce map outputs. GIS provides an opportunity to decision makers to understand problems, appreciate solutions, and examine problems through spatial analysis. GIS thus works as an aid to the decision support system of users. Since rice is the major crop of the country and it has been experiencing a decline or stagnation in yield, an intimate understanding of the individual rice ecosystems is of primary importance. Demonstrations that could be made are the manifestation of that. Much more could be done for sustainable rice production if commitment, dedication, intellect, and resources were combined.

Conclusions

The flood-prone areas of Bangladesh (minus tidal and estuarine floodplains, as they are not considered for the purposes of this paper) provide ample opportunities for growing different varieties of rice in different seasons of the year. Nevertheless, the choice of variety as well as the season of rice production are largely governed by hydrological characteristics and the frequency of occurrence of natural hazards. Besides hydrology, soil characteristics such as soil texture, fertility, permeability, availability and quality of irrigation water, and management are the other important factors that influence rice productivity. Further, except for boro paddy, rice in Bangladesh is generally grown under rainfed conditions. Thus, rainfall characteristics (amount

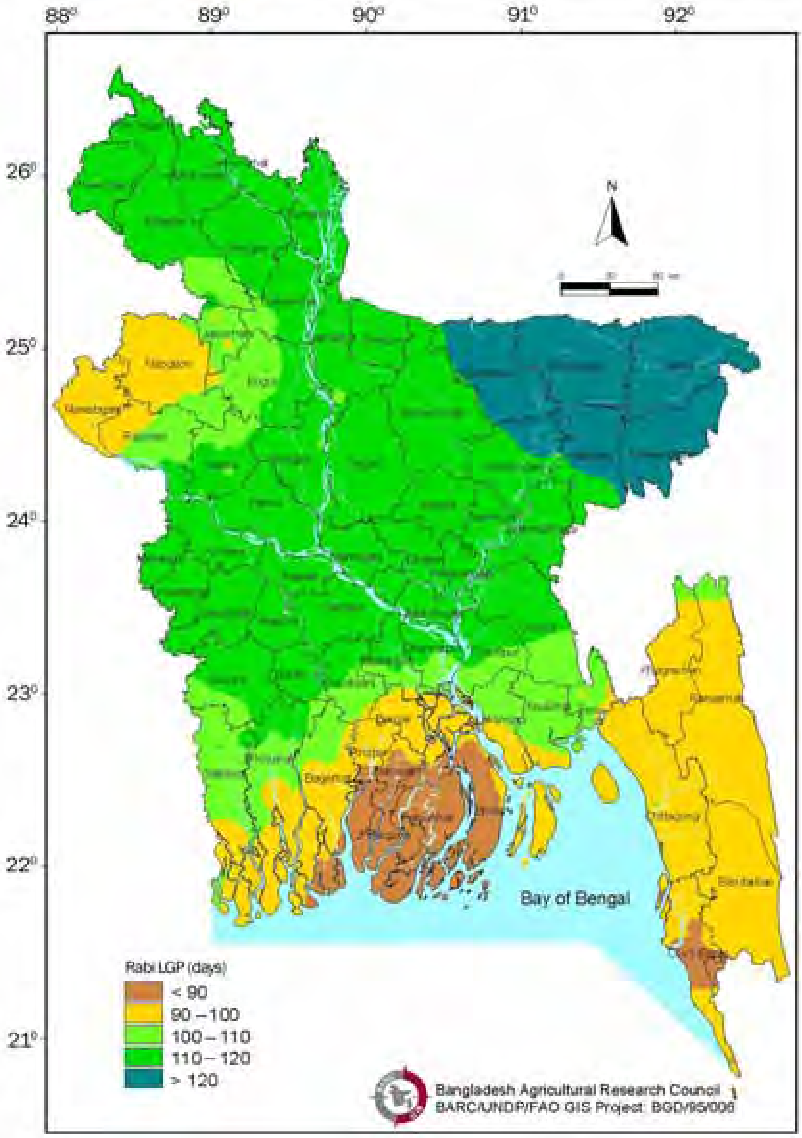


Fig. 13. Reference for rabi length of growing period in Bangladesh.

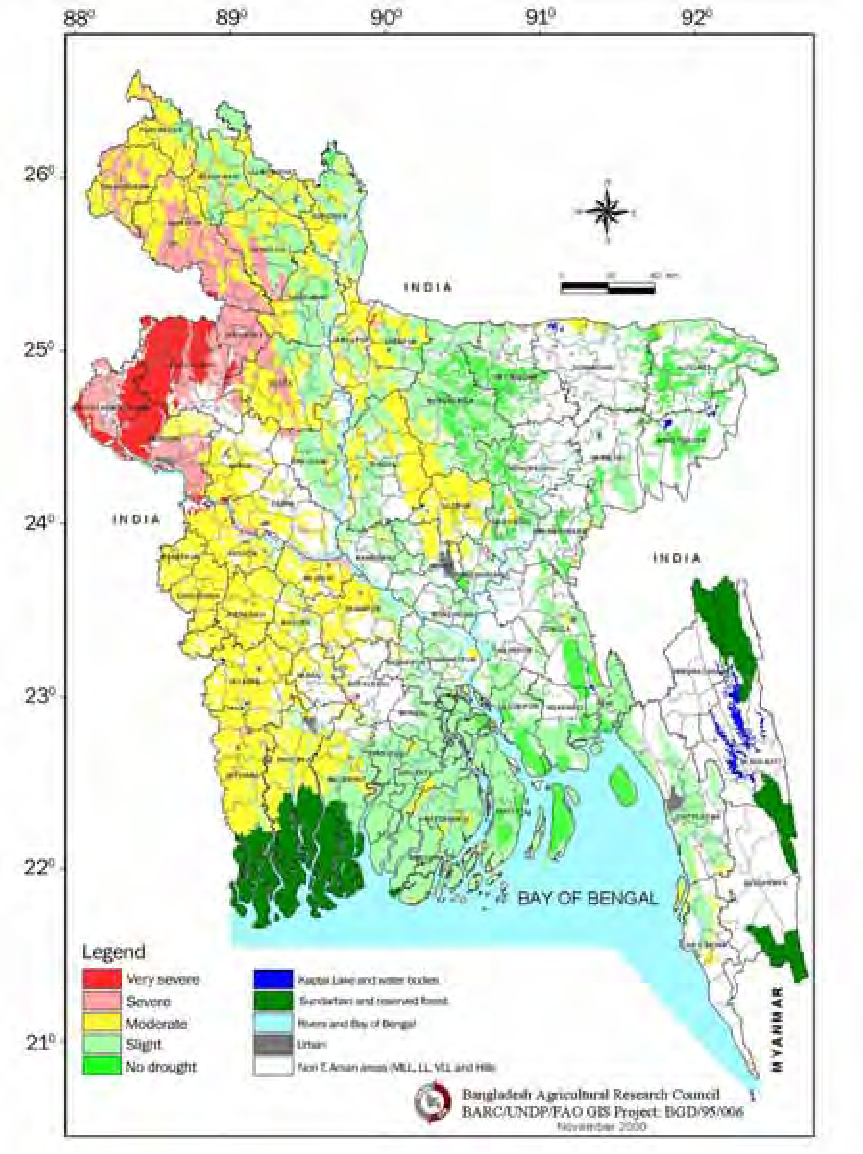
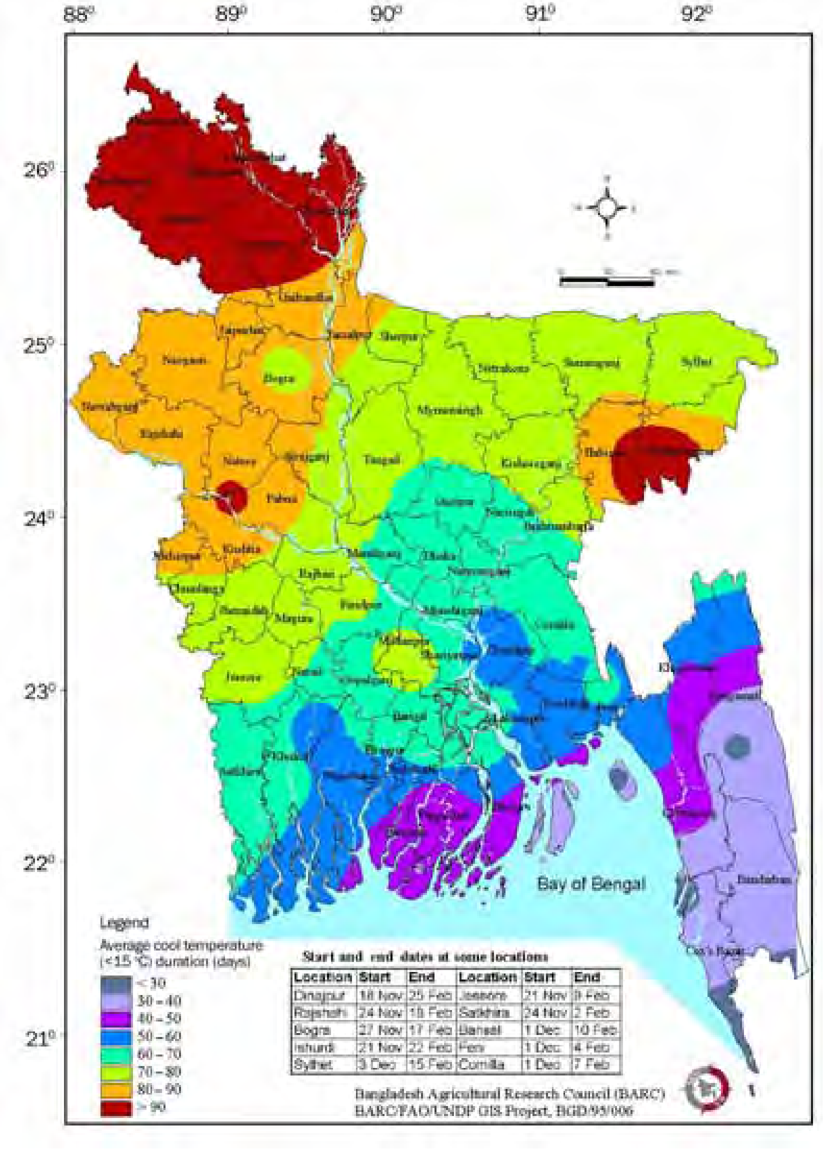


Fig. 14. Kharif (T. aman) drought-prone areas in Bangladesh.



Start and end dates at some locations

Location	Start	End	Location	Start	End
Dinajpur	18 Nov	25 Feb	Jessore	21 Nov	9 Feb
Rajshahi	24 Nov	15 Feb	Satkhira	24 Nov	2 Feb
Bogra	27 Nov	17 Feb	Barisal	1 Dec	10 Feb
Ishurdi	21 Nov	22 Feb	Feni	1 Dec	4 Feb
Sylhet	3 Dec	15 Feb	Comilla	1 Dec	7 Feb

Fig. 15. Average cool temperature (<15 °C) duration in Bangladesh.

and distribution pattern) play a decisive role. In other words, agroecological characteristics with spatial and temporal variability actually determine different levels of suitability of the rice crops in Bangladesh.

From the socioeconomic point of view (preference of rice as a matter of cultural setup, food security, and food habit), rice will perhaps continue to retain priority over other crops in area. As a result, it will enjoy decided preference, not only in the kharif-1 and kharif-2 seasons but also in the dry rabi season, in spite of the much-needed diversification of cropping. The rice-based pattern needs to be tailored with at least one nonrice crop where possible with a view to producing and providing nutrition to the malnourished millions, reducing dependency on the import of pulses and oilseed crops, conserving soil health, and sustaining land productivity.

The monoculture of paddy, especially in the irrigation project areas, without allowing proper aeration of land, has already created physical (lowering of structural stability/load-bearing capacity), chemical (zinc, sulfur, boron, and other nutrient deficiencies), and biological (decline in benign microbial populations) problems. Further, monoculture of paddy with its shallow fibrous root system causes continuous nutrient mining from the upper few-centimeters-thick and fertile soil without allowing recycling from the underlying subsoil. This is a serious soil resilience problem, particularly in the face of growing cultivation of modern rice varieties without judicious fertilizer application by most resource-poor farmers of the country.

The recent revelation of the decline or stagnation in yield of modern rice varieties is a manifestation of that. The average yield of MV aman and boro rice had no significant changes from 1970-71 to 1999-2000, whereas the yield of MV aus has decreased gradually (Mustafi and Azad 2000). Imbalanced fertilization, improper soil-crop-water management practices, the nonavailability of desired technology and the inadequate adoption of modern technologies, the increase in the cost of production, degradation of soil, and the lack of a favorable policy environment are responsible for such a situation. Appropriate rice technology needs to be developed for the 1.9 million ha of deeply flooded areas and 0.51 million ha of active flood-prone (*char*) areas of the country. Rice scientists need to focus more on developing high-yielding varieties and making tangible advances in developing hybrid rice varieties suitable for the different agroecosystems of the country. Locally suited technologies need to be further improved and adopted. With the predicted change in climate, the extent and duration of inundation will be much more. With the rise in temperature and higher evapotranspiration, the drought effect will be highly pronounced. Research thus needs to be reoriented to adjust to this changed situation. Rice scientists, extensionists, and NGO personnel need to work in harmony to combat upcoming problems.

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Notes

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Current status and strategies for increasing the productivity of single- and double-rice production systems in deepwater areas of Bangladesh

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About 30% of the net cultivated land of Bangladesh annually floods deeper than 1.0 m. Farmers have little option to grow crops during the monsoon other than deepwater rice (DWR). In the late 1960s, deepwater rice grew on about 21% (2.09 million ha) of the rice land and contributed about 14–16% to the total rice production. From the beginning of the Green Revolution era, farmers started to grow high-yielding modern rice varieties (MVs) in the dry season and abandoned DWR cropping because boro rice yields were 2–3 times greater than those of DWR. Some farmers in different areas are trying to grow DWR after boro, but success has so far been limited. They mostly establish DWR seeds by broadcasting, and the time available between seeding and flooding is usually not enough for the survival of DWR plants under a rising water level. Therefore, DWR after boro often fails or produces poor yields. Thus, this practice has not expanded or gained popularity. About 1.3 million ha of deepwater land now remain fallow during the monsoon. However, research has shown that the boro-DWR pattern is feasible if the DWR crop is established by transplanting mature seedlings following a cut-off date. Such a pattern can produce 2.0 t ha^{-1} of additional yield over the boro-fallow pattern. These unused DWR areas have the potential to produce about 2.5 million tons of paddy. The cut-off dates for seeding and transplanting of boro and cut-off date for DWR transplanting in different floodplains are suggested, and tips for good performance of this pattern are also given. Research strategies followed in the past for developing DWR varieties are discussed. It is recognized that developing high-yielding modern DWR varieties for >1.0-m water depth is not possible. An appropriate strategy for DWR varietal improvement has been suggested. The new strategy aims to increase yield by 15–20% for location-specific traditional DWR varieties by improving yield components without affecting elongation ability and photosensitivity.

Bangladesh is a country of rivers and flat plains, with less than 10% of the land more than 30 m above sea level (Yeo 1982). The Ganges-Brahmaputra-Meghna river systems form the world's largest delta (Catling 1992). Eighty percent of Bangladeshi land is floodplain, 12% hill area, and 8% terraces (FAO 1988). Flood is a natural annual phenomenon in Bangladesh. It is estimated that 50% of Bangladesh's land area of 14.49 million ha is vulnerable to floods and in an exceptional year floods may

Table 1. Topography of cultivated lands (land type) with suitable major crops of Bangladesh during the monsoon (kharif II) season.

Land type		Flooding depth[a] (cm)	Total area		Net cultivated land	
			Million ha	%	Million ha	%
Highland	(F_0)	0–30*	4.20	29.0	3.26	36.1
Medium highland	(F_1)	30–90 **	5.04	34.8	3.15	34.9
Medium lowland	(F_2)	90–180**	1.77	12.2	1.43	15.8
Lowland	(F_3)	180+ **	1.10	7.6	1.11	12.3
Very lowland	(F_4)	180+ ***	0.19	1.3	0.08	0.9
Total soil area			12.30	84.9	9.03	100.0
River, urban, homesteads, etc.			2.18	15.1	–	–
Total			14.48	100.0	–	–

[a]* = intermittently flooded, ** = seasonally flooded, suitable for deepwater rice,
*** = seasonally flooded, not suitable for DWR.
Source: Adopted from MPO (1987) and FAO (1988).

submerge more than 60% of the area (Karim and Iqbal 1997). In a typical year, 30% of the net cultivated area floods deeper than 1 m.

In the mid-1980s, about 15% of the total land was under rivers, urban areas, homesteads, etc. (FAO 1988). Of the total soil area (12.3 million ha), 29.0% was highland (F_0), 34.8% medium highland (F_1), 12.2% medium lowland (F_2), 7.6% lowland (F_3), and 1.3% very lowland (F_4, Table 1). Net cultivated area under these land types was 3.26, 3.15, 1.43, 1.11, and 0.08 million ha, respectively. Some deepwater rice grows in medium highland, where seasonal flooding depth varies from 30 to 90 cm. Deepwater rice is predominant in medium lowland (90–180-cm water depth) and lowland (180+-cm water depth) but very lowland area is not suitable for it (MPO 1987). However, since then, more than one million ha of net cultivated area have become occupied by urban area, homesteads, etc. (Islam 2000).

Flooding patterns

The onset of flooding and maximum water depth vary considerably between years (Tables 2 and 3). The onset of flooding may vary by 3–9 weeks between years. Flooding starts in early to mid-June in the eastern parts (Meghna floodplain) and in mid-June to July on the Jamuna and Ganges floodplains of the central parts of the country (Catling et al 1983). The rate of water rise is usually rapid, 8–10 cm per day for the first 50 cm of flooding, 5–8 cm per day from 50 to 100 cm, and 4–6 cm per day to 150 cm, and is quite variable from 150 to 300 cm (Catling 1992). The maximum water depth varies considerably between locations (from a few cm to more than 4 m). The maximum depths are normally reached in mid- to late August on the Meghna and Jamuna floodplains and about 3–4 weeks later on the Ganges floodplain. The peaks are usually sharp.

Table 2. Onset of flooding in rice fields and maximum water depth in different sites and years.

Floodplain	Location	Year	Onset of flooding	Maximum depth (cm)
Meghna	Demra, Dhaka	1983	1 July	153
		1984	2 June	209
		1985	18 June	138
	Sonargaon, Narayanganj	1986	1 July	151
		1987	20 June	298
		1988	28 May	346
Jamuna	Keraniganj, Dhaka	1977	10 June	219
		1978	18 June	176
		1979	7 July	184
		1980	17 June	329
	Mirzapur, Tangail	1982	2 July	162
		1983	8 July	214
		1984	6 June	260
		1985	3 July	196

Table 3. Mean date of flood inundation and maximum water depth in deepwater rice fields in different floodplains during 1977 to 1980.

Attribute	Year	Observations (no.)	Floodplain			
			Meghna	Jamuna	Ganges	Mean
Flood inundation	1977	58	16 June	21 June	22 June	20 June
	1978	53	18 June	27 June	2 July	26 June
	1979	71	17 June	16 July	12 July	5 July
Water depth (cm)	1977	63	168	171	174	171
	1978	54	149	155	140	148
	1979	71	168	152	174	165
	1980	52	201	274	246	240

The flood recession phase is more consistent in timing and rate than the onset of flooding (Catling 1992). Water usually subsides fairly rapidly following the last flood peak. Depending on the topography, recession usually ends from the end of October to the end of November. The total flooding period usually lasts for 4 to 6 months. Flooding pattern, especially the time of the onset of flooding, the rate of increase, maximum depth, and water recession, has profound effects on the evolution, selection, and adoption of deepwater rice (DWR) varieties. Flooding pattern varies between floodplains, locations within floodplains, and topographic situations within locations. Therefore, hundreds of landraces or cultivars (500–600, Hasanuzzaman 1974) were selected and adopted by our ancestors in Bangladesh.

Table 4. Distribution of deepwater rice area in greater districts of Bangladesh (1972).

Greater district	DWR coverage (ha)	Share of DWR in district (%)	Proportion of total DWR (%)
Faridpur	314,413	55.6	15.1
Comilla	257,306	38.5	12.3
Sylhet	226,194	27.7	10.8
Dhaka	212,024	38.6	10.2
Pabna	183,522	43.4	8.8
Rajshahi	154,210	23.5	7.4
Mymensingh	150,445	11.4	7.2
Jessore	135,709	31.2	6.5
Tangail	100,162	33.4	4.8
Noakhali	83,117	13.7	4.0
Khulna	76,275	13.2	3.7
Barisal	72,591	11.7	3.5
Kushtia	48,259	23.3	2.3
Rangpur	26,640	4.0	1.3
Chittagong	21,134	0.3	1.0
Dinajpur	15,587	1.7	0.8
Bogra	8,583	2.4	0.4
Chittagong Hill Tract	1,012	1.0	0.1
Patuakhali	0	0	0
Total	2,087,181	21.0	100.0

Source: Adopted from Ahmed (1974) and Hasanuzzaman (1974).

Deepwater rice: past and present

The International Rice Research Institute (1984) defined rice growing in water depths from 50 to 100 cm as deepwater rice and above 100 cm as very deepwater rice, whereas Catling (1992) termed very deepwater rice as floating rice. According to this terminology, rice grown in deep water in Bangladesh is mostly floating rice or very deepwater rice. The name deepwater rice is used herein as it is widely used and the crop is grown in deep waters in Bangladesh. Deepwater rice also has several local names—broadcast aman, jolidhan, poushdhan, etc.

Before the 1970s, deepwater rice was one of the important crops of Bangladesh, occupying about 20% of rice lands and contributing about 14–16% of the total rice production (Ahmed 1974, Hasanuzzaman 1974). Deepwater rice areas are mostly concentrated in the middle part of the country. This was the most important rice crop in greater Faridpur (55.6% of rice area), Pabna (43.4%), Dhaka (38.6%), Comilla (38.5%), Tangail (33.4%), Jessore (31.2%), Sylhet (27.7%), Rajshahi (23.5%), and Kushtia (23.3%) districts (Table 4). Some DWR is grown in all other districts, except Patuakhali.

As the demand for rice grew, alternatives were sought, and farmers started to shift from deepwater rice to dry-season boro rice in the early 1970s (Ahmed 1974, Hasanuzzaman 1974). In three decades, DWR coverage decreased by about 63%

Table 5. Trend of area, production, and yield of deepwater rice in Bangladesh.

Years	Area (million ha)	Area reduction over 1969-70 (%)	Production (million t)[a]	Yield (t ha^{-1})[a]
1969-70	2.086	–	2.169	1.04
1970-71	1.824	12.6	1.642	0.90
1971-72	1.774	15.0	1.508	0.85
1972-73	1.870	10.4	1.533	0.82
1973-74	1.834	12.1	1.614	0.88
1974-75	1.639	21.4	1.295	0.79
1975-76	1.831	12.2	1.794	0.98
1976-77	1.740	16.6	1.583	0.91
1977-78	1.686	19.2	1.703	1.01
1978-79	1.681	19.4	1.664	0.99
1979-80	1.231	41.0	1.477	1.20
1980-81	1.575	24.5	1.496	0.95
1981-82	1.586	24.0	1.634	1.03
1982-83	1.547	25.8	1.547	1.00
1983-84	1.464	29.8	1.537	1.05
1984-85	1.233	40.9	1.233	1.00
1985-86	1.355	35.0	1.423	1.05
1986-87	1.349	35.3	1.349	1.00
1987-88	1.230	41.0	1.119	0.91
1988-89	0.934	55.2	0.803	0.86
1989-90	0.943	54.8	1.037	1.10
1990-91	0.938	55.0	0.994	1.06
1991-92	0.839	59.8	0.856	1.02
1992-93	0.907	56.5	0.943	1.04
1993-94	0.907	56.5	0.943	1.04
1994-95	0.856	59.0	0.779	0.91
1995-96	0.836	59.9	0.786	0.94
1996-97	0.840	59.7	0.865	1.03
1997-98	0.810	61.2	0.770	0.95
1998-99	0.601	71.2	0.535	0.89
1999-2000	0.775	62.9	0.860	1.11

[a] Refers to clean rice.

mainly because of the expansion of MV boro rice in DW areas (Table 5). This conversion materialized through the development of irrigation facilities (mainly shallow tubewells) in deepwater rice areas. As a result, rice production jumped from 1 t to about 4 t ha^{-1}. After the boro harvest, most of the land remains fallow and submerged during monsoon. Now, about 1.31 million ha of deepwater lands remain unused during monsoon.

Boro-DWR: a potential pattern for boosting rice production

As a land-scarce and densely populated developing country, Bangladesh could not afford the luxury of keeping this huge land area fallow for more than 6 months.

Therefore, let us examine whether another crop could be grown after boro rice. As fields remain deeply flooded, scope is limited for crop production other than deepwater rice. DWR is usually planted by broadcasting in March or in the first half of April. If planting is late and flooding starts early in some years, the crop suffers. The key issue, which determines the success of the DWR crop and good yield, is plant age at the time of flood initiation. DWR plants need some time (at least 6 weeks) to acquire elongation ability (BRRI 1974) but for good yield at least 2 months are needed before flooding (Fig. 1, Hasanuzzaman 1974). At least a 2-wk turn-around time is needed after the boro harvest for the establishment of DWR. Thus, at least 10 weeks are needed between the boro harvest and start of flooding. The time available between the boro harvest and onset of flooding often varies from 3 to 8 weeks, and varies between years. Therefore, the boro-DWR pattern is not feasible in the traditional method. Research and field observations show that boro-DWR is possible if DWR is established by the transplanting method following a cut-off date.

The major determinant of DWR production is panicle density. Most Bangladeshi DWR varieties can yield 2.0–2.5 t ha^{-1} paddy if panicle densities are 100–120 m^{-2}. Tiller density increases after planting and reaches a peak before the onset of flooding but decreases consistently from flood initiation to the ripening stage because of flood, stem borer, and rat damage, etc. (Catling et al 1982). To have 100–120 panicles m^{-2}, about 200 elongated tillers m^{-2} at peak flood and about 300 tillers m^{-2} before flood are required.

Careful planning is necessary for the successful production of DWR after boro. As time is limited and crucial, we could transplant older (6 wk) seedlings. A minimum of 3 weeks between DWR establishment by transplanting of 6-wk-old seedlings and the onset of flood could produce good yield. Such indications are clear from Table 6. Field trials in Demra during 1983, 1984, and 1985 clearly indicated that the boro-transplanted DWR pattern has the potential of producing an additional >2.0 t ha^{-1} paddy over the boro-fallow pattern. Therefore, results suggest that the deepwater environment of Bangladesh has the potential of producing about 2.5 million t of additional paddy per year.

The key feature of the boro-DWR pattern: cut-off date for crop establishment

As flood initiation varies considerably between years (Tables 2 and 3) and the time available between boro and flooding is short, it appears that determination of the cut-off date will be very difficult. Based on flooding records at two locations in each of the Meghna and Jamuna floodplains (Table 2), the risk level of crop failure if transplanted at 3-d intervals was calculated (Table 7). When determining the risk level, two assumptions—DWR seedling age of 6 wk and the crop having at least 3 wk before flooding—were made. The risk level was estimated for the situation of maximum water depth up to 250 cm. The cut-off date with a 20% risk level was determined on 12 May for Meghna and 21 May for Jamuna floodplains. As flooding begins in the Ganges floodplain at about the same time as in the Jamuna floodplain (Table 3), the cut-off date for DWR transplanting for the Ganges floodplain was set at 21 May, the same as for the Jamuna floodplain. If farmers transplant 6-wk-old

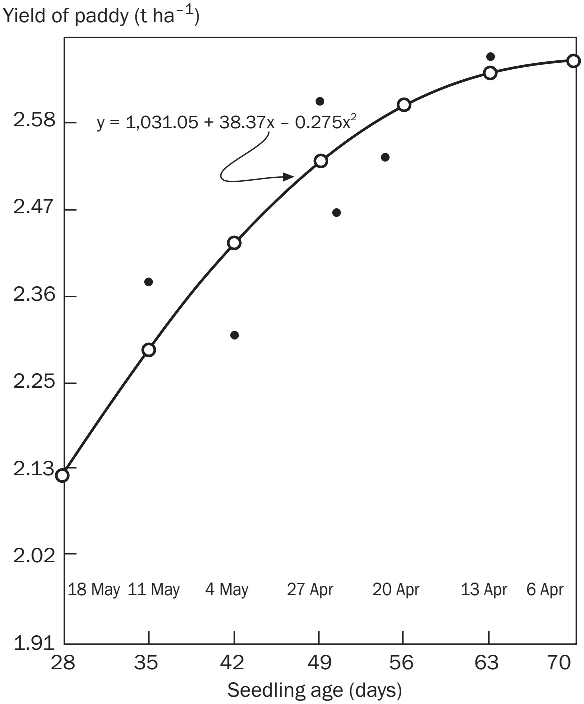

Fig. 1. Relation between seedling age at flooding and yield of deepwater rice. Source: Hasanuzzaman (1974).

Table 6. Performance of transplanted deepwater rice following MV boro in Demra, Dhaka, Bangladesh.

Year	Flooding date	Variety	Seedling age (d)	Days from transplanting to flooding	Elongated stems (no. m^{-2})	Yield (t ha^{-1})
1983	1 July	BR306-B-2-3	48	22	214	1.92
		BR308-B-2-3	34	38	167	1.06
		Gilamyte	34	38	164	2.01
		Kartiksail	35	37	185	1.69
		Sadapankaich	35	37	188	1.61
1984	2 June	BR306-B-2-3	35	5	0	0
		BR308-B-2-3	35	5	0	0
		Gilamyte	34	6	0	0
		Kartiksail	34	5	0	0
		Sadapankaich	34	5	0	0
1985[a]	18 June	Gilamyte	25	27	122	0.58
		Sadapankaich	26	26	93	0.71

[a] Crop suffered severe damage from hispa beetle before flood and damage from aquatic/floating weeds and rats during the flooding period.

Table 7. Estimated risk for deepwater rice crop failure caused by flood vis-à-vis transplanting date in Meghna and Jamuna floodplains. Risk levels were calculated based on 3–4 years of flooding records, 5–6-week-old DWR seedlings, >3-week period between transplanting and flooding in situations of 1.5–2.5-m maximum water depth.

Transplanting date	Risk of crop failure due to flood (%)	
	Meghna floodplain	Jamuna floodplain
1 May	0	0
4 May	0	0
7 May	17	0
10 May	17	0
13 May	33	0
16 May	33	0
19 May	33	12
22 May	33	25
25 May	33	25
28 May	50	50
31 May	67	50
3 June	67	50
6 June	67	50
9 June	67	50
12 June	100	75
15 June	100	75
18 June	100	87
21 June	100	100

DWR seedlings within the cut-off date, the probability of success is 80%. These suggested cut-off dates are tentative and could be refined and developed as location-specific ones if flooding pattern data for several years are available.

To implement these cut-off dates, careful planning is needed to select a boro variety and planting time. Boro rice has to be harvested at least 2 weeks (turn-around time) before the cut-off date of DWR transplanting. The harvest time of the boro will depend on the growth duration of the variety, planting time, and temperature. Therefore, variety-wise cut-off dates for boro seeding and transplanting are needed. The cut-off dates for seeding and transplanting of a few popular boro varieties and DWR transplanting in different floodplains are shown in Table 8.

Present scenario of the boro-DWR pattern

Some farmers are trying to grow DWR after the harvest of boro rice. This practice has been tried since the early 1970s but, so far, success has been limited. Farmers prefer to establish DWR by broadcasting because it requires less effort and labor. The direct-seeded DWR crop has a very low chance of survival except in the year of delayed flooding. In most years, crops either fail or produce very poor yield. Some farmers also establish DWR by transplanting seedlings. But they are not aware of the

Table 8. Suggested approximate cut-off date of transplanting of DWR and preceding MV boro rice in 1.5–2.5-m maximum water depth situations in different floodplains of Bangladesh.[a]

Floodplain	Boro variety	Cut-off date for boro transplanting	Boro harvest date (approx.)	Cut-off date for DWR transplanting
Meghna	BR1	12 Jan	27 Apr	11 May
	Purbachi	12 Jan		
	BR14	7 Jan		
	BRRIdhan 28			
	BRRIdhan 29			
	BR3	28 Dec		
	IR8	28 Dec		
Jamuna	BR1	22 Jan	7 May	21 May
	Purbachi	22 Jan		
	BR14	17 Jan		
	BRRIdhan 28			
	BRRIdhan 29			
	BR3	7 Jan		
	IR8	7 Jan		
Ganges	BR1	31 Jan	16 May	30 May
	Purbachi	31 Jan		
	BR14	26 Jan		
	BRRIdhan 28			
	BRRIdhan 29			
	BR3	16 Jan		
	IR8	16 Jan		

[a] The cut-off date of DWR transplanting in the Ganges floodplain was determined by the historical flooding data and previous table. The 2-week turn-around time between boro and DWR was allowed. Seedling age of 45–50 days for boro varieties was considered.

cut-off date for transplanting and seedling age. Therefore, in most cases, results are not promising. Farmers often grow DWR in scattered fields, which suffer severe damage from floating weeds and debris and a concentration of pests such as rats and stem borers. Because of such uncertainties, DWR cropping following boro has become a casual activity, not a serious business.

In addition, farmers face problems of water for puddling for DWR transplanting. The irrigation system usually shuts down as the boro crop approaches maturity. As yields of DWR are low, owners of tubewells may not be interested in providing irrigation water in exchange for a crop share. Some workable agreement or system needs to be developed for this purpose. In some years, much water will not be required because rainfall starts on time.

Tips for successful DWR production after boro

The following tips can be useful for the successful production of DWR after boro rice in deepwater areas of Bangladesh:

1. Transplant DWR seedlings that are at least 6-wk old before the cut-off date.
2. Use a DWR variety or similar one (in terms of elongation ability and photosensitivity) that is used to grow in a particular field or situation.
3. Transplant DWR seedlings at closer spacing (15 × 15 cm).
4. Use some fertilizer (45 kg N ha^{-1}) at about 10 days after transplanting, which increases plant elongation ability, elongated-tiller density, and yield (Catling 1992). Slow-release forms, such as sulfur-coated urea, are superior to ordinary urea (Catling and Islam 1979).
5. Establish DWR in compact blocks and protect it from floating weeds, debris, rats, and stem borers (if possible).

Rice in isolated fields in open water is usually damaged by floating weeds, debris, and concentrated pests such as rats and stem borers. So, unlike for MV rice, a single-plot demonstration is not useful for transplanted DWR. For good production and demonstration, DWR has to be planted in fairly large compact blocks. An intensive extension effort is needed for the adoption of the boro-DWR pattern. In addition, the use of mass media such as TV and radio would be useful.

Deepwater rice yield and variety

Earlier yield estimates based on a large number of “test cuts” in farmers’ fields reported 1.4 t ha^{-1} (0.9–3.7) paddy (Watt 1891). Based on government reports, Ahmed (1974) reported 1.25 t ha^{-1} (0.99–1.65) paddy yield during the Pakistan era. Some 31 years of data from the Bangladesh Bureau of Statistics indicated the average yield of DWR to be 1.46 t ha^{-1} (1.18–1.79). Extensive crop cuts (291) over four consecutive years from 1977 indicated average paddy yield of 2.25 t ha^{-1}, which varied among varieties, years, and floodplains (Catling et al 1983). Average yields were highest in the Meghna floodplain (2.47 t ha^{-1}) followed by the Ganges (2.19 t ha^{-1}) and Jamuna (1.95 t ha^{-1}). In a favorable situation, such as well-distributed rainfall before flood and gradual flooding, most varieties produced >2.0 t ha^{-1} and some even more than 3.0 t ha^{-1} (Table 9).

How many DWR varieties grew in Bangladesh before the Green Revolution era is not known precisely. However, Hasanuzzaman (1974) and others suspected the existence of 500–600 local DWR varieties. The Green Revolution started in Bangladesh with the introduction of the “miracle rice” (IR8) in 1966. Initially, the major thrust was on MV boro cropping during the dry season in deepwater areas. Therefore, from the beginning of the Green Revolution, DWR coverage started to shrink and varieties to disappear. The rapid erosion of DWR cultivars was reported by Islam (1993) in the early 1990s. Again, how many disappeared and how many are still there are not known. However, from the shrinkage in DWR coverage since the late 1960s, we can assume that about 60% of the DWR local cultivars have probably disappeared during the last three decades.

DWR varietal improvement began in 1917. Initially, the program was implemented through pure-line selection and hybridization started (between local varieties and wild rice) in 1942 (Miah 1990). During the pre-Green Revolution era, nine varieties from pure-line selection and two from the hybridization program were released

Table 9. Yield of different deepwater rice varieties in three major floodplains of Bangladesh in four years from 1977.

Floodplain	Main area	Variety	Samples (no.)	Mean yield (t ha^{-1})	Yield frequency (%)	
					>2.0 t ha^{-1}	>3.0 t ha^{-1}
Meghna	Narsinghdi	Gilamite	8	2.73	100	13
	Gozeria	Gabura	16	1.86	31	0
	Daudkhandi	Pankaish	17	2.89	94	35
	Muradnagar	Kartik Sail	13	2.74	92	46
	Chandina	Ejulikhama	8	2.39	71	29
	Hazigonj	Bodeshor	9	1.73	11	0
	Akhaura	Khama	20	2.78	89	50
Jamuna	Manikgonj Dhaka	Bawalia	11	2.34	73	18
		Choto Bawalia	19	2.44	89	11
		Digha	7	2.45	71	14
		Horhoyra	6	1.87	33	0
		Molla Digha	6	1.94	50	0
		Naptosok	11	1.45	18	0
		Other Bawalia	6	1.82	33	0
	Tangail	Bawalia	6	2.08	50	0
		Chamara	12	1.64	33	0
		Dhola Bawalia	4	2.01	50	17
		Hijol Digha	4	2.37	75	0
Ganges	Faridpur, Madaripur	Lakshmi Digha	21	2.48	90	10
	Pabna, Sirajgonj	Digha	4	1.35	25	0
		Puiatapari	14	1.72	29	0
		Sarsari	24	2.51	67	25
	Natore	Sail Kota	16	1.83	38	0

Source: Catling et al (1983).

(Table 10). Among these, Habigonj aman varieties are mainly restricted to the Habigonj area, whereas Gabura is popular in some areas of the Meghna floodplain (Gozeria, Sonargaon, etc.). However, during 291 crop cuts and pest surveys from 1977 to 1980, none of these varieties, except Gabura, was encountered.

Crosses between local DWR varieties and high-yielding semidwarf modern varieties (IR8, TKM6) started as early as the 1970s (Choudhury 1974). Later crosses were made between traditional DWR varieties and popular modern varieties (BR3). The DWR breeding program during the last three decades failed to develop and release any variety.

A future strategy for varietal improvement

Some Asian national agricultural research institutes, including BRRI and the International Rice Research Institute, put a lot of efforts into improving DWR through hy-

Table 10. List of improved local deepwater rice varieties released in Bangladesh before the Green Revolution era.

Variety	Selection no.	Parentage	Method	Release year
Baisbis	DA A.I	–	Pure line	1941
Gabura	DA A.II	–	Pure line	1941
Maliabhangar	DA A.III	–	Pure line	1943
Katyabagdar	Hbj.A.I	–	Pure line	1944
Godalaki	Hbj.A.II	–	Pure line	1944
Gowai	Hbj.A.III	–	Pure line	1946
Dudklaki	Hbj.A.IV	–	Pure line	1746
Dhala Aman	Hbj.A.V	–	Pure line	1946
Dhala Aman	Hbj.A.VI	Dhala Aman/Jhora	Hybridization	1950
Dhala Aman	Hbj.A.VII	Laki/Gowai	Hybridization	1951
Lalaman	Hbj.A.VIII	–	Pure line	1952

Source: Miah (1990).

bridization between local DWR/floating rice and semidwarf high-yielding varieties. So far, some achievements have been made in 50–100-/120-cm water depth situations, particularly in Thailand. But nothing resulted for a deeper situation, which is more relevant for Bangladesh. The objectives of hybridization between semidwarf MVs and floating rice to develop higher-yielding floating rice were not well thought out and this does not seem possible. One cannot have a high harvest index for floating rice comparable with that of MV rice. For a higher harvest index, we have to sacrifice the elongation ability of floating rice, without which it cannot survive in floodwater.

What strategy should Bangladesh adopt for the future? Is there any scope for improving DWR varieties? Work in Thailand demonstrated great scope for improving DWR for up to 100 to 120-cm water depths. Although most of the Bangladesh DWR areas are flooded deeper than 100 cm, some localized floodwater depths remain within 100 to 120 cm. A breeding program for developing a modern plant type for 100–120-cm water depths appears possible.

A new varietal improvement strategy needs to be adopted for the floating rice of Bangladesh. First, we have to recognize that the cultivation of high-yielding DWR is not possible in a floating rice situation (water depth of 100+ cm). Having recognized that, efforts should be made to improve the yield potential of traditional DWR varieties through pure-line selection and/or hybridization. The program could aim for a 15–20% yield improvement through the improvement of yield components without affecting elongation and photosensitivity. DWR varieties are floodplain-, location-, and topographic position-specific; thus, it is unlikely that a few varieties will perform well in different locations and floodplains. Even in one area, several varieties are needed because of topographic variations between fields. Therefore, a package of DWR varieties is needed for each major DWR area. At the start, we should target several major DWR areas, then collect and improve the major DWR varieties and return seeds of the improved varieties to farmers. The advantage of this process is that breeders do not need to worry about elongation, photosensitivity, and adoption of the variety because improved varieties will be grown where they used to grow. If improvement is done through pure-line selection, the variety release process may not be necessary or applicable. This will give momentum to the process of variety improvement and adoption. If necessary, hybridization and other breeding tools could be adopted; in that case, normal variety release steps would probably need to be followed.

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Strategies for increasing the productivity of rice areas affected by flash flood

M.K. Mondal, A.F.M. Saleh, M.N. Hassan, and S.I. Bhuiyan

The northeast region of Bangladesh receives the highest rainfall and a huge discharge from the rivers flowing down from the hills of Assam and Meghalaya, India. As a result, the region is flooded to several meters for 6–7 months of the year. Flash floods in the piedmont rivers of the region, which are common during the premonsoon months of April and May, spill over the banks and eventually flow into the flood basins and *haors*, causing extensive damage to dry-season boro rice, which is at or near harvest. About 60% of the total haor areas drained by 31 January are suitable for high-yielding variety (HYV) boro rice cultivation and the rest for traditional rice cultivation, unless excess water is drained out artificially. The construction of submersible embankments around haor areas on the basis of a one-in-ten-year premonsoon flood level occurring before 15 May is the only engineering option for the protection of the crops from flash floods. Presently, HYV coverage in the boro season is low in haor areas. When excess water is drained out by January, the agronomic option is to complete transplantation of a 140–145-day HYV rice crop (e.g., BRRIdhan 28, BRRIdhan 36) by 31 January with about 60-day-old seedlings. Relatively longer duration BRRIdhan 29 can be grown in those areas drained by mid-January. The crops can be harvested by the end of April. Thus, the danger of crop damage from flash flood could be minimized and a safe harvest could be ensured with about 5–7 t ha^{-1} paddy yield. The development of a cold-tolerant rice variety would help reduce the growth period of rice and improve productivity in these areas.

The government should construct submersible embankments around haors with an adequate culvert for navigation, and responsibility for operation and maintenance of embankments could be transferred to the farmers' groups in a planned manner. Farmers should also be trained so that they can adopt appropriate crop and water management strategies for improving productivity of the haor areas.

The northeast region of Bangladesh (Fig. 1) has an area of 24,200 km^2 (about 17.5% of the total area of the country) and is dominated by flood basins and *haors,* which are large saucer-shaped seasonally flooded interfluvial depressions. Small permanent water bodies, locally called *beels*, occupy the lowest pockets within the haors. During the premonsoon and monsoon, the region receives the highest rainfall in the country,

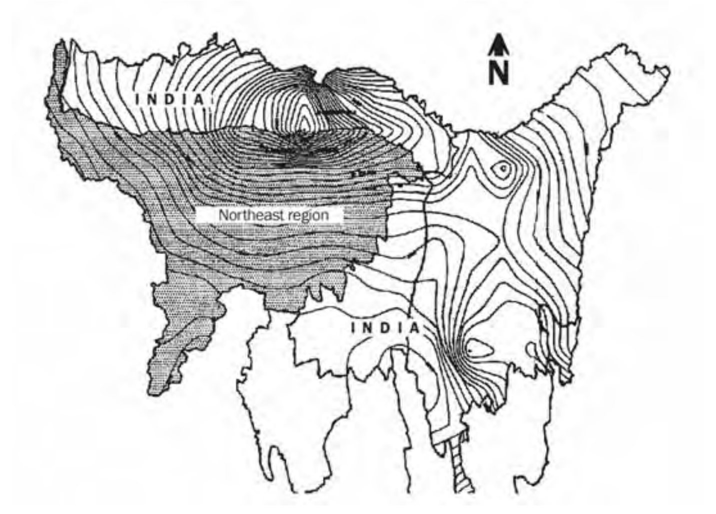

Fig. 1. The northeast region of Bangladesh, showing mean annual rainfall, 1961-90.

varying from 2,200 mm in the west to 5,800 mm in the northeast. The region also receives a huge discharge from the rivers flowing down from the hills of Assam and Meghalaya in India. As a result, the basin is flooded to several meters for 6–7 months of the year. In the winter season, most of the water drains out, leaving small isolated beels in this region.

As more than two-thirds of the cultivable lands of the region are medium to deeply flooded, agricultural production has always been associated with the risks of flooding. Agricultural production has been increasing by 1% annually during the past decade, but it has not kept pace with the regional population growth rate of 1.9% during the same period (FAP6 1993). Most of the region is monocropped with rice, which occupies more than 82% of the total cropped area. About two-thirds of the total rice cropped area is under low-yielding traditional varieties.

The physical setting and hydrology have produced a unique water regime in the northeast region. Flash floods in the piedmont rivers of the region, characterized by a steep rise and rapid recession of the water level, are common during the premonsoon months of April and May. The duration of the high flood stage is short, often less than a week. The rapidly rising flash floods spill over the banks and eventually flow into the flood basins and haors, causing extensive damage to dry-season boro rice, which is at or near harvest.

Economic development in this region is synonymous with the development of its water resources, which play an important and vital role in agro-socioeconomic development of the haor areas. Flood protection is one of the key factors in this development process. But the opportunities for full flood protection are very limited because of the large flood depth and the consequent colossal size of the embankment area required for flood conservation, traditional boat communication, and fishing and the high cost of drainage by pumping (BWDB 1994). Therefore, submersible embankments were constructed around the haors to delay the flooding and protect crops from the premonsoon flash floods. The submersible embankments are much smaller in size and have higher economic returns than full flood embankments and do not affect the regional flood status (Saleh 1991). There are 21 such projects in the region, with 900 km of submersible embankments (Salehin and Saleh 1997). But, the subsequent drainage congestion caused by construction of embankments and sedimentation in the rivers have delayed transplantation of boro rice during the winter season in the protected areas and narrowed down its growing period. This paper examines the opportunities for improving land productivity of the region affected by flash floods.

Climate and hydrology of the northeast region

Climate

The northeast region enjoys a tropical monsoon climate with two distinct seasons: the cold and dry winter season and the hot and wet monsoon season. The mean winter temperature during December-January varies from 17 to 19 ^oC and during the monsoon from 27 to 28 ^oC. The mean monthly maximum and minimum temperatures at Srimangal, which is situated in the southern part of the region and is one of the coldest areas of the country, are 10.4 and 8.5 ^oC during December and January, respectively. The mean monthly hours of bright sunshine at Sylhet are the highest during the winter months and vary from 7.8 h in December to 9.0 h in February. The average monthly relative humidity (about 85%) and wind speed (about 6 km h^{-1}) are highest during the monsoon months. The relative humidity is the lowest during March (about 58%) and the wind speed is the lowest during December (about 2 km h^{-1}).

Surface water

The surface water hydrology of the haor area is controlled by the three main river systems. The Surma and Kushiyara rivers drain the eastern part, the Kangsha River drains the western part, and the Kalni and Baulai rivers drain the central part. All these rivers discharge into the Meghna River and have vast catchment areas outside Bangladesh in the Himalayan Mountain ranges. The estimated total surface-water supply to the region is 173 km^3, of which 40% originates as rainfall over the region (FAP6 1993). Only about 5% of the total surface-water supply is available during the dry winter season (December-April).

The rivers of the region are characterized by devastating flash floods in the basins during the premonsoon when the flows rise to a high peak in a few days and also recede rapidly. Figure 2 shows the hydrographs of the Kalni River at Markuli showing flash floods and annual floods. Flash floods usually flow through the haor area during the ripening and harvesting stages of boro rice and severely damage the crop. Flash floods also bring and deposit huge quantities of sediment on agricultural lands and river beds, creating drainage problems during the postmonsoon period.

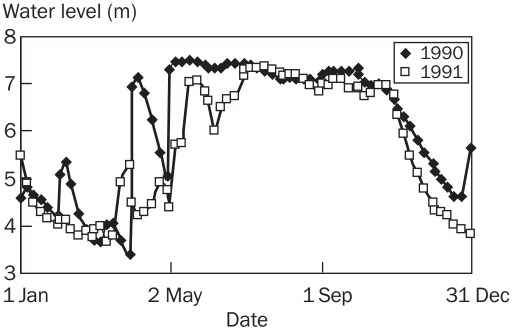

Fig. 2. Hydrographs showing normal conditions (1991) and flash flood (1990) in the Kalni River at Markuli.

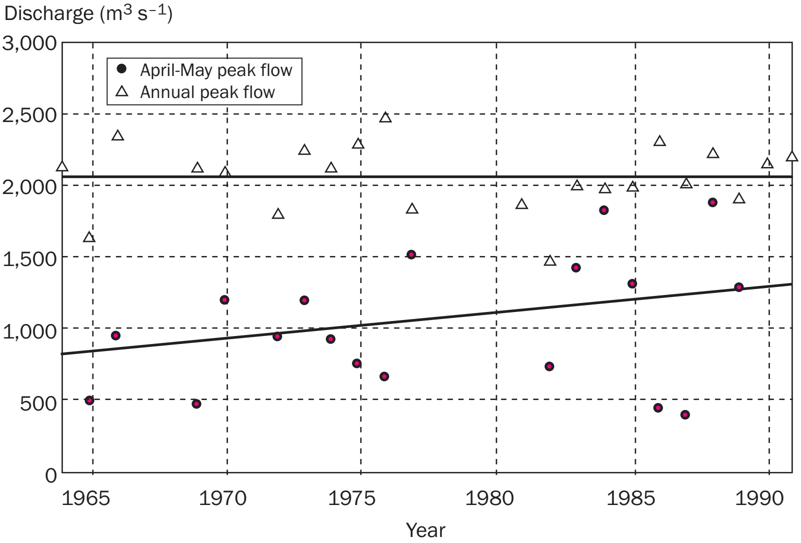

Fig. 3. Trend of premonsoon and annual peak flows of the Surma River in Sylhet.

The main monsoon flood peaks generally occur from August to October. On average yearly, about 60% of the region is inundated to a depth of 1 m or more during the peak monsoon period. Deep flooding during the monsoon, flash flooding during the premonsoon, and deposition of sediments on agricultural lands are some of the major constraints to agricultural development in the region.

Analysis of data of premonsoon peaks of the rivers of the region shows an increasing trend. For some of the rivers, such as the Surma in Sylhet, the premonsoon peak flows are nearing the annual peak flows in recent years (Fig. 3). This seems to be dangerous for the boro-season rice in the haor areas in terms of vulnerability to flash floods. Continuous polderization in the region and siltation of the river beds are primarily responsible for such an increasing trend (EGIS 1998).

Groundwater

Little is known about the groundwater status of the northeast region of Bangladesh, as the area as a whole has not been extensively explored for groundwater development. Analysis of available data indicates that aquifers are semiconfined to confined in nature, with low average transmissivity (about 800 $m^2\ d^{-1}$) and hydraulic conductivity (about 25 $m\ d^{-1}$) compared with those of other parts of the country (MPO 1984). Therefore, the potential of groundwater development for irrigation seems to be limited in this region.

Rainfall

The haor areas of Bangladesh have a typical tropical monsoon climate. Rainfall is abundant and the amount is increasing northeastward and reaching a maximum on the south-facing slopes of the Shillong plateau (Fig. 1). Average annual rainfall at Habiganj, Sylhet, and Sunamganj is 2,630, 3,920, and 5,360 mm, respectively. However, most of the rainfall occurred during the monsoon season, spanning June to September. Analysis of 10-day rainfall totals of Sunamgonj from 1961 to 1993 showed that rainfall was very scanty during October to March and that, at the 80% dependable level, rainfall is practically zero.

Soil types and agricultural practices

The present soil structure of the northeast region is the result of sedimentation from alluvial and colluvial deposits of the main river systems of this region (BWDB 1994). The soils are gray, olive gray, sometimes dark to greenish gray, loam to silty clay loam and silty clay loam to clay soils on ridges and basin margins, together with gray and shallowly developed clay soils in perennially submerged to wet basins. The major components of the general soil types of this region are (1) noncalcareous gray floodplain soil, (2) acid basin clay, and (3) noncalcareous alluvium soil (BARC 1989). These soils are extremely acidic in nature (pH <5.0), but sometimes become alkaline or neutral to medium acidic when noncalcareous alluvium soils are drained. Soil layers, which remain perennially wet, are neutral in reaction in field conditions.

Organic matter contents ranged from 0.5% to 2.0% in ridge soils and from 2% to 4% in basin soil. Soils generally have 2–5% organic matter in the cultivated layer, which means that most agricultural soils are rich in organic matter compared to other parts of the country.

In general, soil texture in this region falls under clay and loam categories. About 50–70% of the soils in this region are clayey and about 30–50% are loamy in texture and are suitable for rice cultivation. Although most soils remain wet in the dry season because of rice cultivation, the soil that dries out becomes very hard and widely cracked.

As in other parts of the country, most lands (80–85%) of the northeast region are used for crop cultivation. Most agricultural activities in this region are concentrated in the dry season, spanning December to May. Where irrigation facilities are available, modern high-yielding rice varieties are grown; otherwise, traditional low-yielding varieties are cultivated, using fewer crop management practices in the majority of the land area. Nonrice crops such as wheat, potato, pulses, sweet potato, chilli, vegetables, oilseed, and spices are grown on a limited scale (2–5% of land area) on the relatively higher land by using residual soil moisture.

Some farmers cultivate low-yielding broadcast aman in medium-low land to lowland where floodwater rises 180 cm or more during the peak flood period spanning March to June (BWDB 1994). This crop is sometimes inundated because of early flash flood and/or uprooted by wave action and is damaged either partially or fully.

In the Chaptir haor area, highland and medium highland occupy only 1% of the total land area, where T. aman rice and nonrice crops are grown. These lands are located near the homesteads. Medium lowland, lowland, and very lowland occupy about 80% of the total land area where the major crop is boro rice, most of which is low-yielding traditional rice. HYV boro rice is grown on about 10% of the land area. Also, there is evidence that farmers cultivated HYV boro rice on about 50% of the medium lands and medium highlands in the Sunamgonj region, where surface water is available for irrigation (BWDB 1995). Among the modern rice varieties, BR12, BR14, BR19, and BR26 are popularly grown in the haor areas. BWDB (1995) observed that BR26 was gaining popularity owing to its shorter duration in comparison with that of other modern rice varieties. Average yields of local boro and HYV boro rice varieties were about 2.0 and 3.0 t ha^{-1}, respectively (BWDB 1995), which seem low. BRRI-developed (1999) recent rice varieties yielded much higher in farmers' fields of haor areas. Therefore, there is potential for increasing the productivity of the haor areas experiencing flash floods every year by adopting appropriate rice varieties and agronomic practices.

Flash-flood protection measures

The average elevation of most agricultural lands in the northeast region of Bangladesh is below 8.0 m and they are flooded to a depth of 5.0 m or above. To live and to produce rice, farmers in this region have adopted different flash-flood protection measures. Construction of submersible embankments around a haor area is the most common flood protection measure adopted historically by farmers, especially by large landowners. The embankments' design criteria, particularly the embankment height, were taken arbitrarily from their experience, and the embankments varied from 4 to 6 m depending on the location of the haor. In most cases, these embankments could protect boro rice from flash flood, but were very vulnerable to breaches. When breaches occur because of flash floods, losses are fully expected. In normal years, about 20–25% crop losses were inevitable because of the combined effects of local rainfall and flash floods.

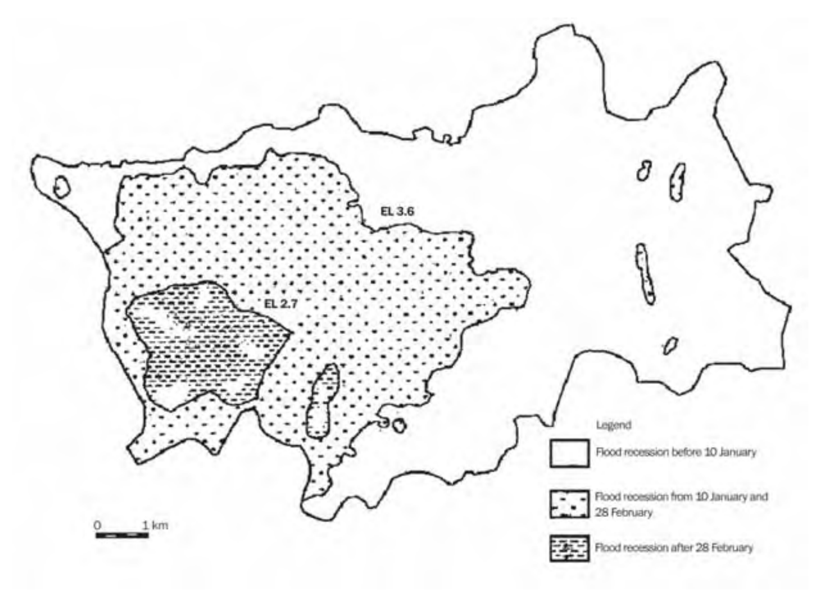

Fig. 4. Floodwater recession pattern of Shanir haor.

Strategies for increasing productivity of the northeast region

Engineering approach

During monsoon, most areas of the northeast region remain completely inundated. Postmonsoon drainage usually starts in October, with the recession of river water levels, and continues up to February. The haor areas are suffering more and more from delayed postmonsoon drainage because of slow drainage through the regulators/sluices, sedimentation, and siltation of the rivers, which delay transplantation of boro rice. Late transplanting not only reduces rice yield (BRRI 2000) but also increases the probability of crop damage caused by flash flood. Ultimately, HYV boro rice, which requires higher investments for fertilizer and irrigation, is increasingly becoming a high-risk crop. Thus, the potential HYV rice area is being limited to the highlands that can be drained in early January. Figure 4 shows the drained area at different times after the recession of floodwater in a typical haor of the region, Shanir haor. About 60% of the area drains within January and becomes suitable for transplanting HYV boro rice. The rest of the area remains inundated till the end of February and is not suitable for HYV boro rice cultivation. A similar analysis carried out for Chaptir haor shows that floodwater recedes from about 90% of the haor area by 31 January and becomes suitable for HYV boro rice cultivation. The rest, 10% of the area, remains inundated beyond January and is unsuitable for HYV boro rice cultivation. Therefore, we can generalize that about 60% of the total haor areas are suitable for HYV boro rice cultivation and in the rest of the areas HYV boro rice cannot be grown unless excess water is drained out artificially. Appropriate flash-flood protection measures should be undertaken along with timely draining out of excess water to increase rice productivity in these areas through the adoption of modern varieties. Either excess water should be pumped out by 31 January or short-duration local boro rice varieties should be grown in these areas.

Crop damage caused by early flash flood has become more frequent in recent years (BWDB 1994). In the past 40 years, the peak water level in the haor area rose by 0.3 m during the premonsoon period, which resulted in more insecurity toward early flooding. Consequently, boro rice in haor areas is currently being inundated more frequently than before. Moreover, premonsoon rainfall resulted in greater drainage congestion (BWDB 1993a,b) because of the increased volume of rainwater accumulated in the lower part of the haors during April-May. Drainage by gravity at this time is simply impossible because of higher water levels in the river. All these factors are also detrimental to the adoption of HYV rice in these areas.

To protect boro rice from flash floods, the farmers and Bangladesh Water Development Board (BWDB) constructed submersible embankments of various heights (4–6 m). BWDB (1994) proposed that submersible embankments in the haor areas be designed on the basis of a 1 in 10-year premonsoon flood level that is expected to occur before 15 May. It is recommended that submersible embankments have a 3.0-m crest width and 1:3 side slopes. Relatively flat side slopes were chosen to reduce erosion caused by overtopping and wave action and to improve stability of the embankments.

But, it was observed that most submersible embankments are poorly constructed and are not fully capable of protecting boro rice. Erosion of the embankment during overtopping by flood flow, which occurs every year, and scarcity of suitable soil for resectioning are probably the main reasons for insufficient embankment heights. Moreover, erosion caused by persistent wave action and man-made breaches in the embankments for navigation/boat crossing and to alleviate drainage congestion have also deteriorated the performance of the submersible embankments.

Construction of properly designed and adequately maintained submersible embankments around haors is the only engineering option for protecting the crops from flash floods and increasing the productivity of the haor areas.

Agronomic approach

By natural drainage, a majority of the land (about 60% of haor areas) becomes suitable for HYV boro rice cultivation within January. Then, by using 60-day-old seedlings, relatively shorter duration high-yielding rice varieties such as BRRIdhan 28 and BRRIdhan 36 can be successfully grown in the haor areas. Even the more high-yielding long-duration variety BRRIdhan 29 can also be grown in lands where floodwater drains out within the first half of January. The rice crops can be harvested by the end of April, with reduced risk of damage by flash flood. Cultivation of the abovementioned HYV boro varieties in haor areas could increase production to about

5–7 t ha^{-1} (BRRI 1999) compared with the present production of 3–4 t ha^{-1}. Khan et al (1999) showed that rice production has increased by about 28% in the Zilkar haor area because of protection from flash flood by submersible embankments. They attributed the gain in production to the increased adoption of HYV rice in the project area compared with the preembankment period.

It has already been mentioned that the haor areas are comparatively cooler than the rest of the country during the winter months (December-January). Thus, the development of more HYV rice varieties with more cold-tolerance characteristics would provide a wider choice to farmers and would help to increase the productivity of the haor areas affected by flash floods.

Organizational approach

Traditionally, farmers of the haor areas are cooperative and very quick in their farm operations, especially in transplanting rice. Farmers' organizations could accelerate the process of adopting appropriate agronomic and engineering strategies. It was observed that the government could not provide funds for operation and maintenance activities adequately. Therefore, the government should take charge of construction of the submersible embankments and the responsibility for operation and maintenance of the embankments could be transferred to the farmers' groups in a planned manner. Farmers in other parts of the country are shouldering all irrigation-related expenses for crop production, without any subsidy from the government. Once the farmers in haor areas would see the protection measures for the crop, they would cooperate with the government and agree to bear all operation and maintenance expenses of the embankments. Thus, productivity of haor areas of the northeast region could be increased significantly through both vertical and horizontal expansion.

Conclusions and recommendations

Two strategic options are available to improve productivity of the areas affected by flash floods. One is the engineering approach, that is, protection of flash flood by submersible embankments. The second one is the agronomic approach, that is, to introduce high-yielding varieties of rice that would mature and be harvested before the occurrence of flash floods in late April to early May. Another option is to combine the two, which would give farmers a wider variety choice.

Postmonsoon drainage is the most critical factor for improving the productivity of the rice lands of haor areas in the northeast region of Bangladesh. Appropriate agricultural technologies, especially relatively short-duration high-yielding rice varieties, are presently available (e.g., BRRIdhan 28 and BRRIdhan 36). If excess water can be drained out by January, transplanting could be completed with 60-day-old seedlings. Then, a 140–150-day rice crop could be harvested by the end of April with about 5–7 t ha^{-1} paddy yield. Thus, the danger of crop damage by flash flood could be minimized and a safe harvest ensured.

More higher-yielding varieties that mature early are needed for these areas. The introduction of cold tolerance to the rice through an appropriate breeding process should help to reduce the growth period of rice in these areas.

Damage of crops by flash flood can be minimized by constructing submersible embankments around haor areas. The government should properly construct submersible embankments around haors with adequate provisions for drainage and navigation. The responsibility for operation and maintenance of embankments could be transferred to farmers' groups in a planned manner. Then, the farmers could adopt an appropriate strategy for improving the productivity of the haor areas.

In addition, the inputs needed for cultivating HYV rice should be made available to the local market and farmers should be trained on their use for improving the productivity of the rice lands of haor areas. Moreover, the government should encourage farmers to plant trees along the submersible embankments to reduce erosion and in turn to minimize repair and maintenance costs of the embankments.

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Opportunities for nonrice crops in flood-prone environments

Md. Nur-E-Elahi and Md. Akhter H. Khan

The lands of Bangladesh have been broadly classified into flood-prone and flood-free, using land appraisal and cropping pattern survey data. The Rice Farming Systems (RFS) Division of the Bangladesh Rice Research Institute has established the net area covered by rice and nonrice crops grown in different land categories of flood-prone and flood-free environments. About 1.01 million ha remain fallow during the rabi season of seven farming systems and potential opportunities exist for nonrice crops in the flood-prone environment. Moreover, 722,000 ha have the potential to increase the yield of nonrice crops through the application of modern technologies.

The lands of Bangladesh, based on flooding depth, have been classified into the highland (above flood level), medium highland-1 (flooded up to 30 cm), medium highland-2 (flooded up to 90 cm), medium lowland (flooded up to 180 cm), lowland (flooded up to 300 cm), and very lowland (flooded greater than 300 cm) (FAO/UNDP 1998). But, the area covered by crops in different farming systems of these land categories was not available. The Rice Farming Systems (RFS) Division of the Bangladesh Rice Research Institute (BRRI) has estimated the area for these land categories (Elahi et al 1999) through a nation-wide cropping pattern survey.

The flood-prone environment and nonrice crops are the two key subjects of this paper. We determined the area of flood-prone land categories excluding tidal wetland saline and nonsaline environments (Fig. 1). A 60-cm seasonal flooding depth is considered the beginning point of the flood-prone environment. In FAO/UNDP data, flood-prone lands cover about 4.91 million ha; for the crop-based data, this area is about 4.5 million ha. Figure 2 depicts a map of Bangladesh showing the extent of flood-prone lands.

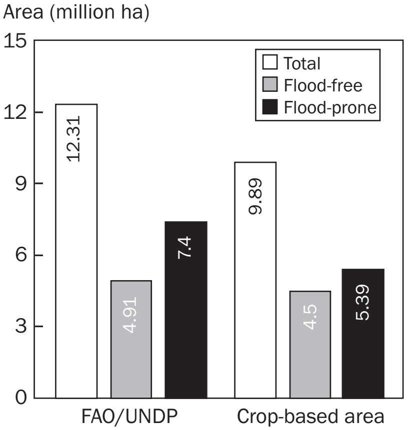

Fig. 1. Flood-free and flood-prone land area in Bangladesh.

Figure 3 shows the area distribution in different flood-prone land categories of FAO/UNDP and crop-based data. The area calculated from the crop-based data for different flood-prone land categories is very close to that of the FAO/UNDP data.

In the flood-prone environment, no other nonrice crops could be grown during kharif-1 and kharif-2 seasons except jute because of flooding behavior in the environment. Only the nonrice field crops grown during the rabi season and jute, in kharif-1, have been included in this paper. Table 1 describes the range of seeding and harvesting times of nonrice field crops and jute in different rabi seasons. All pulses, spices, vegetables, groundnut, linseed, sesame, sweet potato, millet, and melon have been grouped as rabi crops. Sugarcane, a perennial field crop, has not been discussed in this paper.

Area and production scenario of nonrice crops

We highlight the area and production scenario of the nonrice crops of Bangladesh for 1993-94 to 1997-98. These data cover both the flood-free and flood-prone lands. For simplicity, nonrice cereals, timbers, pulses, oilseeds, spices, and winter vegetables have been lumped into their respective groups except jute and wheat (Figs. 4–11).

Wheat area has increased by 0.2 million ha from 1993-94 to 1997-98 and production by about 0.7 million metric tons (Fig. 4). The area under other nonrice cereals remained unchanged, but production tended to decline (Fig. 5). Area under tubers has not changed over time, but production showed an increasing trend (Fig. 6). The area and production of jute declined sharply in 1995-96 compared with 1994-95. Thereafter, the area and production have increased sharply (Fig. 7). An almost static trend in area and production has been observed for pulses (Fig. 8), oilseeds (Fig. 9), and spices (Fig. 10). Though the area of winter vegetables has not changed much, their production has increased gradually (Fig. 11).

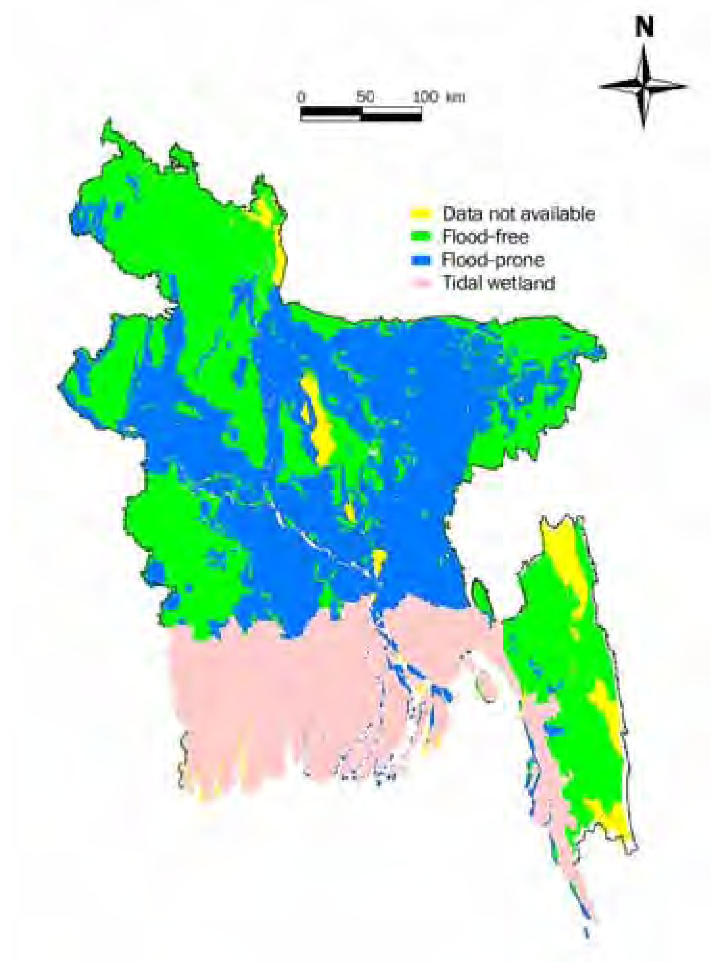

Fig. 2. Map of Bangladesh showing the extent of flood-prone and flood-free land.

Figures 12 and 13 present the area and production of rice and nonrice crops of 1997-98. Rice covered 78% of the total cropped area and represented 74% of the total crop production. Among the nonrice crops, pulses covered 6% of the area, followed by wheat (5%) and oilseeds (4%). Similarly, tuber crops had the highest production share (7%) and spices the lowest (1%). Wheat had a 6% share of the total crop production.

The data mentioned above clearly suggest scope for increasing the area and production of nonrice crops to reduce the gap between the requirement and produc-

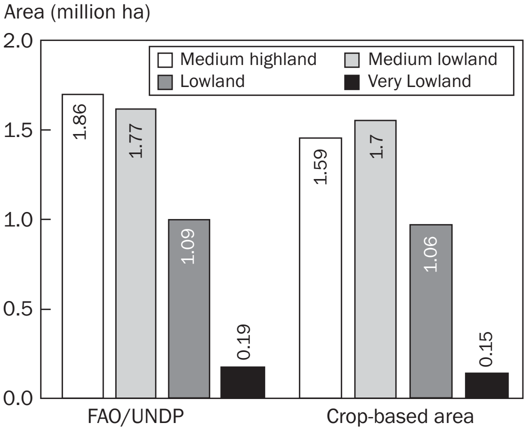

Fig. 3. Area distribution in different flood-prone land categories.

Table 1. Seeding and harvesting time of different nonrice field crops during the rabi season.

Group	Crop	Seeding time	Harvesting time
Cereals	Wheat	Mid-November-mid December	March
	Maize	October-November	February-March
	Indian millet	Mid-November-mid-February	Mid-February-mid-May
Spices	Onion	October-December	February-April
	Garlic	October-December	March-April
	Chilli	September-October	January-March
	Coriander	October-December	March
Oilseeds	Mustard	October-November	February-March
	Sesame	October-November	March-April
	Linseed	October-November	February-March
	Groundnut	October-December	May-June
Pulses	Khesari	Mid-October-mid-November	February-March
	Lentil	Mid-October-mid November	Mid-February-mid-March
	Chickpea	Mid-November-mid-December	February-March
Tuber crops	Potato	October-mid-January	December-March
	Sweet potato	Mid-October-mid-November	March-April
Fiber crop	Jute: Deshi	March-April	June-mid-September
	Tosa	April-May	June-mid-September
Fruit crops	Watermelon	December-March	March-June
	Muskmelon	December-March	March-May
Vegetable crops	Sweet gourd	Mid-November-mid-December	March-April
	Radish	September-December	November-February
	Cauliflower	September-December	November-February
	Cabbage	October-December	December-March
	Tomato	October-December	November-April
	Brinjal	September-November	November-April

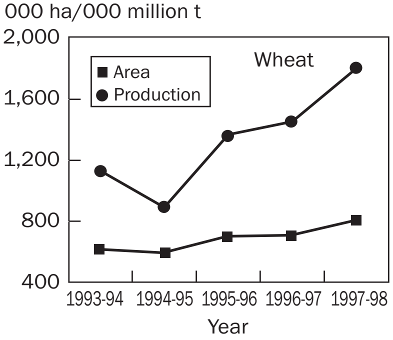

Fig. 4. Area and production trend of wheat, BBS (1998).

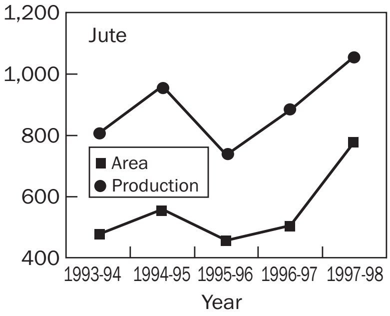

Fig. 7. Area and production trend of jute, BBS (1998).

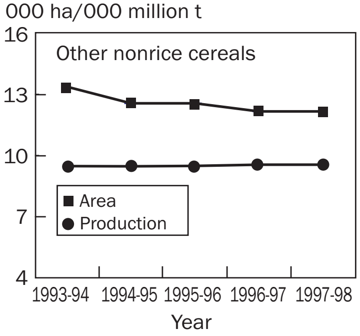

Fig. 5. Area and production trend of other nonrice cereals, BBS (1998).

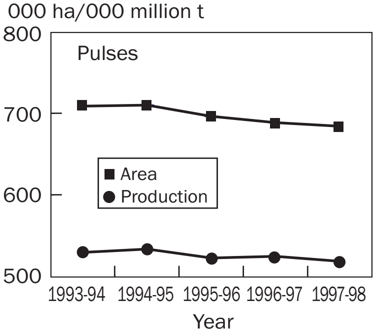

Fig. 8. Area and production trend of pulses, BBS (1998).

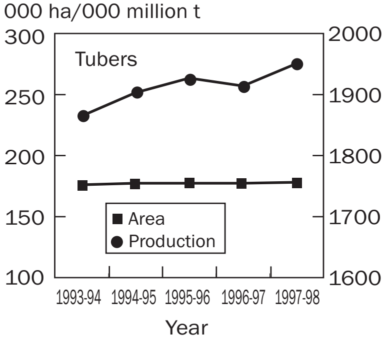

Fig. 6. Area and production trend of tubers, BBS (1998).

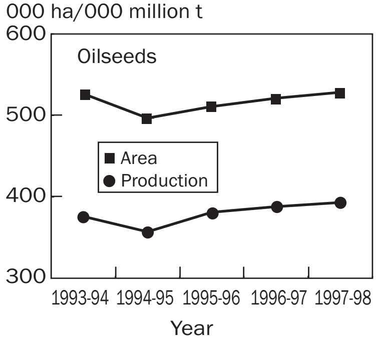

Fig. 9. Area and production trend of oilseeds, BBS (1998).

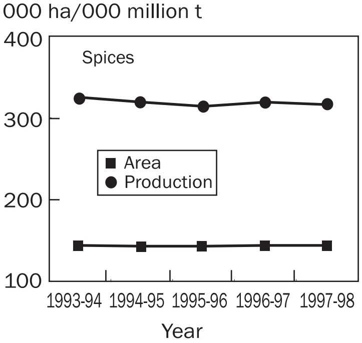

Fig. 10. Area and production trend of spices, BBS (1998).

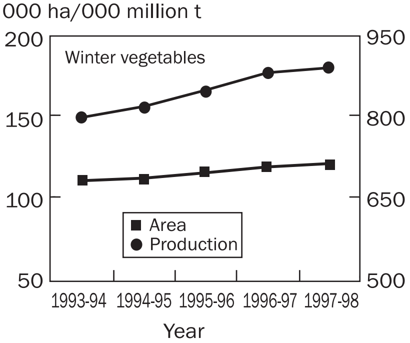

Fig. 11. Area and production trend of winter vegetables, BBS (1998).

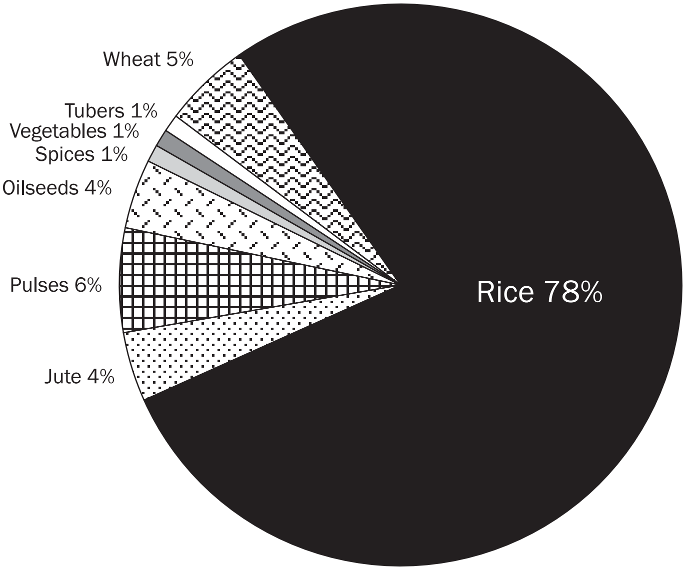

Fig. 12. Area share of rice and nonrice field crops, BBS (1998).

tion of the country. To achieve the target, avenues have to be explored from both flood-free and flood-prone lands.

Net rice and nonrice crop area in flood-prone lands

Area coverage statistics in rice and different nonrice crops for different flood-free and flood-prone land categories were not available. Table 2 presents the area under rice and nonrice crops such as wheat, jute, rabi crops, potato, and mustard for differ-

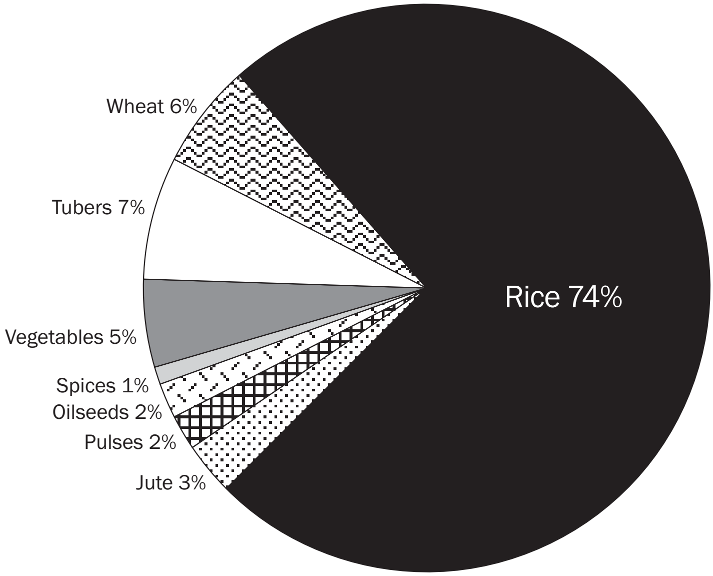

Fig. 13. Production share of rice and nonrice field crops, BBS (1998).

Table 2. Net rice and nonrice crop area in different flood-free and flood-prone land categories.

Land category	Area (million ha)					
	Rice	Wheat	Jute	Rabi crops[a]	Potato	Mustard
Flood-free						
Highland	1.40	0.25	0.17	0.37	0.004	0.013
Medium highland (1)	2.50	0.16	0.11	0.33	0.061	0.028
Subtotal	3.9 (56)[b]	0.41 (59)	0.28 (56)	0.70 (56)	0.065 (41)	0.041 (14)
Flood-prone						
Medium highland (2)	0.90	0.23	0.18	0.19	0.03	0.06
Medium lowland	1.09	0.06	0.04	0.31	0.03	0.17
Lowland	0.96	0.002	–	0.06	0.035	0.012
Very lowland	0.15	–	–	–	–	–
Subtotal	3.10 (44)	0.29 (41)	0.22 (44)	0.56 (44)	0.095 (59)	0.242 (86)
Grand total	7.00	0.70	0.50	1.26	0.16	0.28

[a] Rabi crops included lentil, chickpea, khesari, blackgram, onion, garlic, coriander, chilli, vegetables, millet, and sweet potato. [b] Numbers within parentheses indicate percent area.
Source: Cropping pattern survey 1996-97.

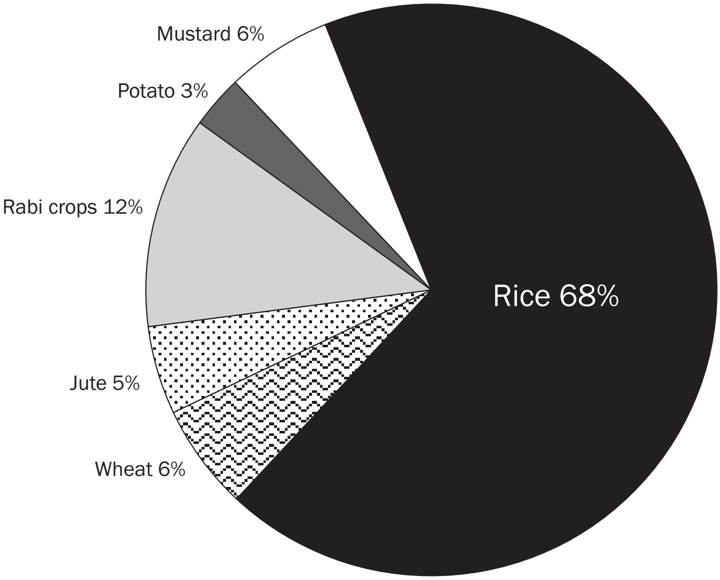

Fig. 14. Net area share of different crops on flood-prone lands.

ent land categories in two environments, which have been produced from the cropping pattern survey data. Rice area coverage in all land categories is higher compared with that of other nonrice crops. In the flood-free environment, rice area is also higher (56%) than in the flood-prone situation (44%). Similarly, the area of wheat, jute, and rabi crops is also higher in the flood-free environment than in the flood-prone environment. However, the reverse scenario is observed for potato and mustard. Among the nonrice crops, area coverage for the rabi crops in the flood-prone environment is the highest (0.56 million ha). Wheat (0.29 million ha) ranked second and mustard (0.242 million ha) third. Furthermore, in the flood-prone environment, rice still covered more area (68%) than the nonrice crops (Fig. 14). This situation clearly explains the necessity of exploring the opportunities for exploiting more area that had remained fallow in the existing farming systems.

Opportunities of nonrice crops in the farming systems of the flood-prone environment

Two strategies for exploiting the opportunities of nonrice crops for flood-prone environments are to (1) bring more area under nonrice crops and (2) increase the current yield levels of nonrice crops already being cultivated in the existing farming systems.

For the first strategy, the flood-prone environment has about 1.01 million ha under seven farming systems: fallow–T. aus–T. aman; fallow–B. aus–T. aman; fallow–fallow–T. aman; fallow–deepwater aman; fallow–B. aus + B. aman; boro–fal-

Table 3. Area (ha) under farming systems having opportunities for nonrice crop cultivation in different flood-prone land categories.

Farming systems	Flood-prone land category		
	Medium highland (2)	Medium lowland	Lowland
Fallow–T. aus–T. aman	79,460	57,500	–
Fallow–B. aus–T. aman	94,505	75,200	–
Fallow–fallow–T. aman	80,521	–	–
Fallow–deepwater aman	–	58,103	223,009
Fallow–B. aus + B. aman	–	–	11,800
Boro–fallow–T. aman	168,340	–	–
Boro–fallow–fallow	–	165,655	–
Total	422,826	356,458	234,809

Source: Cropping pattern survey 1996-97.

low–T. aman; and boro–fallow–fallow. In these systems, opportunities exist for cultivating nonrice crops during the rabi season (Table 3). Table 4 describes the conditions that determine the possibility of cultivating nonrice rabi crops in different flood-prone lands. If we could create conditions favorable for crop establishment, a large part of the 1 million ha could be brought under nonrice crops during the rabi season. Moreover, farmers' needs, market demand, and the value and maturity of the nonrice crops should be taken into consideration when choosing nonrice crops or varieties for this environment. This could be done through a systems-oriented participatory research and extension effort. Research conducted by the RFS Division of BRRI on the possibility of cultivating nonrice crops in the short fallow period (about 70 days) after the T. aman harvest and before boro rice transplanting in the boro–fallow–T. aman pattern showed that this was possible (Elahi et al 1999). Potato (Cv. Hira), legume vegetables (BARI motor-2 and Jharseem-1), and mustard (Improved Tori-7) have been identified as having potential for cultivation in this short period. About 170,000 ha having a 70-day fallow period in the boro–fallow–T. aman system have an opportunity for cultivating nonrice crops in the flood-prone environment. This requires a farmers' participatory demonstration effort by researchers and extension agencies.

In the second strategy, on about 722,000 ha of land, farmers are already cultivating wheat, potato, mustard, and other rabi crops in different farming systems of flood-prone lands (Table 5). The yields of these crops are low compared with the national average yield (Table 6). However, at the research level, the yields of these crops are higher with modern management packages. The application of modern technologies on the 722,000 ha where wheat, potato, mustard, and rabi crops are already being grown would provide an opportunity for increasing productivity to a greater extent.

Table 4. Flooding behavior and soil physical characteristics of different flood-prone lands.

Flood-prone lands	Flooding behavior		Soil physical characteristics	
	Initiation time	Recession time	Soil type	Moisture regime during rabi season
Medium highland (2)	July	September to clay	Sandy loam	Soil having good texture and moisture; if crop establishment is in time, crop performs well. Established crop may suffer from moisture stress. Rain in late October may delay establishment of rabi crops and these crops perform poorly. Delayed harvesting of preceding rice may delay establishment of rabi crops and these perform poorly.
Medium lowland	June	October	Loam to silty clay loam	Soil with good texture and moisture facilitates establishment of rabi crops. Too much moisture at the time of establishment of rabi crops. When soil moisture becomes optimum, crop establishment is late. With time, soil moisture becomes depleted and tillage becomes difficult. Established crops may suffer from drought with time.
Lowland	May	Mid-October-mid-November	Loam to silty clay	Same conditions prevail in the medium lowland.
Very lowland	Mid-April	December	Silty clay	Saturated soil and excess standing water leave no opportunities for nonrice crops.

Table 5. Area under different nonrice crop-based farming systems in the flood-prone lands.

Farming systems	Area (ha)
Wheat–jute/aus/DW aman/F–T. aman/F	290,000
Potato–jute/boro/DW aman/F–T. aman/F	95,000
Mustard–boro–T. aman/F	242,000
Rabi crops[a]–jute/aus/DW aman/B. aus + B. aman–T. aman/F	95,000
Total	722,000

[a] Rabi crops included lentil, chickpea, khesari, blackgram, onion, garlic, coriander, vegetables, and chili.
F = fallow, DW = deepwater.
Source: Cropping pattern survey 1996-97.

Table 6. Yield of different nonrice crops, 1993-98.

Crops	Yield (t ha^{-1})					
	1993-94	1994-95	1995-96	1996-97	1997-98	Av
Cereals						
Wheat	1.84	1.50	1.95	2.05	2.24	1.92
Maize	1.06	1.06	1.06	1.23	1.23	1.13
Joar	1.15	1.13	1.18	1.33	1.33	1.22
Barley	0.59	0.64	0.64	0.64	0.64	0.63
Pulses						
Lentil	0.81	0.81	0.83	0.83	0.79	0.81
Mungbean	0.56	0.59	0.58	0.62	0.62	0.59
Chickpea	0.73	0.73	0.72	0.72	0.71	0.72
Blackgram	0.77	0.78	0.77	0.78	0.76	0.77
Oilseeds						
Rape and mustard	0.71	0.71	0.76	0.74	0.74	0.73
Sesame	0.60	0.62	0.61	0.61	0.61	0.61
Linseed	0.64	0.67	0.65	0.71	0.71	0.68
Groundnut	1.15	1.09	1.12	1.15	1.15	1.13
Spices						
Chilli	0.81	0.80	0.79	0.78	0.80	0.80
Onion	4.18	4.18	4.06	4.13	4.01	4.11
Garlic	3.09	3.09	3.01	3.01	3.09	3.06
Tubers						
Potato	10.96	11.16	11.27	11.25	11.38	11.20
Fibers						
Jute	1.68	1.72	1.61	1.74	1.35	1.62

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Notes

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Rice-fish production systems in flood-prone environments: current status, constraints to increasing productivity, and mitigation strategies

M.G. Hussain, A.H.M. Kohinoor, A.B.M.M. Haque, and M.A. Mazid

Fish-rice culture is considered an ideal method of land use since the land is used to produce both rice and fish. Fish-rice culture is now developing rapidly in many countries in Asia. In Bangladesh, rice-fish culture has been gaining in popularity. Our study focused on the production potential of fish in the flood-prone ecosystem. The study was undertaken during 1998, 1999, and 2000 at Kuliarchar, Brahambaria, Narail, and Muktagacha sites attached to various river floodplains. The range of production of the different sites during 1998 was 75 to 528 kg ha^{-1} and in 1999 154 to 817 kg ha^{-1}. In 2000, harvesting was not yet completed though the estimated production in the 5-month culture period of different sites was 426 to 1,956 kg ha^{-1}. Fish production in both concurrent and alternative flood-prone ecosystems was higher than in previous years. The results of our study clearly indicated that a large potential exists for substantially increasing fish production in the deepwater flood-prone ecosystem in Bangladesh.

In the agro-based economy of Bangladesh, fisheries play an important role in nutrition, employment, and foreign exchange earnings, contributing 5% to gross domestic product, 10% to export earnings, and 60% to animal protein intake, in addition to providing 1.4 million people full-time employment and 11 million part-time employment. The current level of fish and shrimp production (1998-99) of Bangladesh is about 1.5 million tons, 78% of which comes from inland waters and 22% from marine waters. The country consists of deltaic plains dominated by the main river systems such as the Ganges, the Brahmaputra, and the Meghna; it is endowed with unique water resources comprising both inland (4,339,694 ha) and marine (16,607,000 ha) waters. The vast water resources of the country are rich in diversity of fish species.

Bangladesh is ideally suited for integrating aquaculture with rice farming. Of the total rice area, some 1.36 million ha are blessed with underground aquifers that supply deep and shallow tubewells for year-round rice production. In addition, deepwater rice area of Bangladesh is estimated at 2.4 million ha (Catling et al 1987), of which 1.40 million ha are B. aman or floating rice. With the recent availability of irrigation facilities, either from ground or surface sources, and the introduction of high-yielding varieties of boro rice, most farmers shifted to irrigated or boro rice cultivation (Ali et al 1993). Deepwater rice areas remain submerged from June to November and are used as a common resource for fishing by the households living around these areas. Because of increasing fishing pressure and environmental degradation, resulting in a loss of fish breeding and nursery grounds, fish production from these waters is declining at an alarming rate. However, these areas are well suited for fish culture either concurrently with or alternating with rice. Fish culture in rice fields is a low-cost extensive form of aquaculture. To achieve this, attention to water conservation and flood prevention is necessary. Rice yields appear to be enhanced more often than decreased by the introduction of fish into the system (Lightfoot et al 1990).

Various agencies in Bangladesh have undertaken several on-station and on-farm experimental studies over the years on integrating aquaculture with agriculture in the aman and boro season (Haroon et al 1992, Ali et al 1993, CARE 1993, Kohinoor et al 1993, Gupta et al 1996, Gupta 1998). These studies have used a variety of species such as Indian major carp, silver barb, Nile tilapia, and catfish. However, little literature is available on deepwater rice-fish farming in Southeast Asia except Mukhopadhyay et al (1992) and Ali et al (1993). Moreover, no study has been conducted in Bangladesh and elsewhere in Southeast Asia on fish-rice production under the flood-prone ecosystem.

This paper highlights the results of research done under the Bangladesh Fisheries Research Institute (BFRI), Bangladesh Rice Research Institute (BRRI), Proshika, and International Center for Living Aquatic Resources Management (ICLARM) collaborative project on “Fish and rice productivity research in the flood-prone ecosystems of Bangladesh” to evaluate the production potential of fish under polyculture systems in concurrent and alternative cropping management. This paper also briefly discusses the constraints and mitigating strategies for the implementation of fish-rice culture in flood-prone environments.

Polyculture of carp in flood-prone ecosystems

Site selection

Four project areas were selected in three different agroecological zones of Bangladesh. The sites are briefly described as follows:

Kuliarchar. This site is located in the district of Kishoreganj and it represents the Brahmaputra floodplain. The overall hydrological conditions of the sites are explained below:

- **Site 1 (Konapara)**

Farming system: Boro-fallow-boro
Flood initiation time: July
Flooding duration: 3 months
Cause of flood: River water
Soil type: Sandy loam and clay

Popular rice varieties grown in boro season: BR-26, BR-28, BR-29, and Hazishail
Water retention period: 6–7 months
Water depth (max.): 1.5 m
Water depth (min.): 0.6 m
Existing fish species: *Mystus* spp., *Channa* spp., catfish, climbing perch, *Puntius* spp., small prawn, etc.
Fish culture followed: No fish culture yet followed

- **Site 1 (Agarpur)**

Farming system: Boro-fallow-boro
Flood initiation time: July-August
Flooding duration: 2 months
Cause of flood: Rain and river water
Soil type: Clay
Popular rice varieties grown in boro season: Hazishail, BR-26, and BR-28
Water retention period: 6–7 months
Water depth (max.): 1.5 m
Water depth (min.): 0.6 m
Existing fish species: *Mystus* spp., *Channa* spp., catfish, eel, climbing perch, spp., etc.
Fish culture followed: No fish culture yet followed

Brhamanbaria. This site represents the banks of the Meghna floodplain. The overall hydrological conditions of the sites are given below:

- **Site 1 (Urshiura):**

Farming system: Boro-late T. aman (local)
Flood initiation time: June
Flooding duration: 3 months
Cause of flood: River water
Soil type: Clay loam
Popular rice varieties grown in boro season: BR-3, BR-29, IR8, T. aman–Ganja (grown after flood recession in the 3rd week of September)
Water retention period: 4 months
Water depth (max.): 1.0 m
Water depth (min.): 0.5 m
Existing fish species: Carp, eel, small indigenous fish, etc.
Fish culture followed: No fish culture yet followed

- **Site 2 (Uzane Shar):**

Farming system: Single boro
Flood initiation time: Last week of May
Flooding duration: 5 months
Cause of flood: River water
Soil type: Silty clay
Popular rice varieties grown in boro season: BR-14, BR-16, and BR-29
Water retention period: 6–7 months
Water depth (max.): 1.5 m
Water depth (min.): 0.4 m
Existing fish species: Carp, butter catfish, catfish, *Mystus* spp., *Channa* spp., climbing perch, *Puntius* spp., small indigenous fish, etc.
Fish culture followed: No fish culture yet followed

Narail. This site represents the tidal floodplain. The overall hydrological conditions of the sites follow:

- **Site 1 (Sadhukhali)**

Farming system: Boro-transplanted deepwater rice in the lower periphery, boro-T. aman in the upper periphery
Flood initiation time: August
Flooding duration: 5 months
Cause of flood: River water
Soil type: Clay
Popular rice varieties grown in boro season: BR-14 and BR-11
Water retention period: 4–5 months
Water depth (max.): 1.5 m
Water depth (min.): 0.7 m
Existing fish species: *Channa* spp., climbing perch, catfish, *Puntius* spp., etc.
Fish culture followed: No fish culture yet followed

- **Site 2 (Maizpara)**

Farming system: Boro-transplanted deepwater rice
Flood initiation time: June
Flooding duration: 5 months
Cause of flood: River water
Soil type: Heavy clay
Popular rice varieties grown in boro season: Ratna and Gocha
Water retention period: About 5 months

Water depth (max.): 1.0 m
Water depth (min.): 0.5 m
Existing fish species: Common carp, *Channa* spp., climbing perch, catfish, *Puntius* spp., small indigenous fish, etc.
Fish culture followed: No fish culture yet followed.

Muktagacha. The Muktagacha subdistrict is in the district of Mymensingh, which represents the Brahmaputra floodplain. The overall hydrological conditions of the sites follow:

- **Site 1 (Kuripra)**

Farming system: Boro-aman-boro
Flood initiation time: August
Flooding duration: 3 months
Cause of flood: Rainwater
Soil type: Sandy loam
Popular rice varieties grown in boro season and aman season: Chinese IRRI, Aloi, and Morium
Water retention period: 5 months
Water depth (max.): 1.0 m
Water depth (min.): 0.4 m
Existing fish species: *Mystus* spp., *Channa* spp., catfish, Chinese carp, climbing perch, small indigenous fish, common carp, small prawn, etc.
Fish culture followed: No fish culture yet followed.

- **Site 2 (Halida):**

Farming system: Boro-aman-boro
Flood initiation time: July
Flooding duration: 3 months
Cause of flood: Rainwater
Soil type: Clay
Popular rice varieties grown in boro season: BR-11, BR-32, Aloi, and Morium
Water retention period: 5–6 months
Water depth (max.): 1.5 m
Water depth (min.): 0.5 m
Existing fish species: Small indigenous fish, carp, *Mystus* spp., catfish, *Puntius* spp., climbing perch, etc.
Fish culture followed: No fish culture yet followed.

Table 1. Stocking density of different sites during 1998.

Name of area	Stocking density ha^{-1}
Kuliarchar	
Monohorpur	6,250
Bagpara	6,250
Barahambaria Babria	5,500
Narail	4,250

Table 2. Stocking density of different sites during 1999.

Name of area	Stocking density ha^{-1}
Kuliarchar	
Monohorpur	7,627
Charkamalpur	8,774
Barahambaria Babria	
Urshiura	10,926
Uzanishar	7,117
Narail	
Sadhukhali	6,370

Two methods were followed to conduct fish culture in the deepwater rice–fish culture ecosystem: (1) alternative rice-fish culture, followed in B. Babria and Kuliarchar, and (2) concurrent rice-fish culture, in Muktagacha and Narail.

For rice-field preparations in the alternative fish-rice culture system, bamboo enclosures more than 2 m tall were installed in the three open sides of the rice field. But, in the concurrent fish-rice culture system, the dike of the rice fields was strengthened and made 0.75 m high and 0.5 m wide. The opening of the sluice gate was enclosed by a 1.2-m bamboo enclosure.

Carp fingerlings were stocked at all the sites in 1998, 1999, and 2000 in different stocking densities. Details of the stocking density in three consecutive years appear in Tables 1, 2, and 3.

The species combination of fish was maintained on the basis of the hydrological condition of the rice plots. Details of the species combination of the different sites in different years appear in Tables 4, 5, and 6.

For the alternative fish-rice culture management, the fish were stocked in the first week of June, whereas, for concurrent fish-rice management, stocking was done in the third week of June for all three consecutive years, that is, 1998, 1999, and 2000. The culture period depended on the hydrological conditions of the respective sites. At most of the project sites, the culture period varied from 6 to 7 months.

Table 3. Stocking density of different sites during 2000.

Name of area	Stocking density ha^{-1}
Kuliarchar	
Konapara	6,800
Agarpur	5,300
Barahambaria Babria	
Urshiura	5,750
Uzanishar	5,750
Narail	
Sadhukhali	5,500–6,000
Muktagacha	
Halida	5,250–5,875
Kuripara	5,250–5,875

Table 4. Species combination of fish of different sites during 1998.

Name of area	Species stocked						
Kuliarchar							
Monohorpur	Silver carp (19%)	Silver barb (19%)	Carpio (19%)	Rohu (8%)	Catla (19%)	Mrigal (8%)	Grass carp (8%)
Bagpara	Silver carp (25%)	Silver barb (24%)	Carpio (20%)	Rohu (8%)	Catla (8%)	–	Grass carp (15%)
Barahambaria Babria	Silver carp (46%)	Silver barb (28%)	Carpio (14%)	–	–	–	Grass carp (12%)
Narail	Silver carp (9%)	Silver barb (60%)	Carpio (24%)	–	Catla (7%)	–	–

Overall management

Technical and logistic support. Technical assistance for species selection, stocking density, fish sampling, etc., was supported jointly by BFRI scientists and the respective Proshika staff. Proshika provided different kinds of logistic support.

Feeding. Generally, feeding is not practiced in the rice-fish culture system because natural food is available in abundance in the rice-field ecosystem. But, in flood-prone ecosystem management, stocking density was comparatively higher than in the normal fish-rice culture system, so that locally available fish feed such as rice bran was applied at all sites at 1–2% of standing biomass 3–4 days per week during July through October.

Security and monitoring. The landowners of all the project sites formed a committee, which consisted of 10–20 members, under the guidance of the Proshika representative or area coordinator. This committee monitored the field site, feeding, dike

Table 5. Species combination of fish of different sites during 1999.

Name of area	Species stocked						
Kuliarchar							
Monohorpur	Silver carp (14%)	Silver barb (50%)	Carpio (12%)	Rohu (9%)	Catla (12%)	–	Grass carp (4%)
Charkamalpur	Silver carp (14%)	Silver barb (33%)	Carpio (28%)	Rohu (11%)	Catla (14%)	–	–
Barahambaria Babria							
Urshiura	Silver carp (37%)	Silver barb (17%)	Carpio (9%)	Rui (25%)	–	Mrigal (5%)	Grass carp (7%)
Uzanishar	Silver carp (18%)	Silver barb (44%)	Carpio (18%)	Rui (7%)	Catla (13%)	–	–
Narail							
Sadhukhali	Silver carp (16%)	Silver barb (30%)	Carpio (54%)	–	–	–	–

Table 6. Species combination of fish of different sites during 2000.

Name of area	Species stocked						
Kuliarchar							
Konapara	Rui (10%)	Catla (2%)	Mrigal (8%)	Silver carp (8%)	Carpio (15%)	Silver barb (50%)	Grass carp (7%)
Agarpur	Rui (10%)	–	Mrigal (8%)	Silver carp (8%)	Carpio (18%)	Silver barb (56%)	–
Barahambaria Babria							
Urshiura	Rui (8.5%)	Catla (7.0%)	Mrigal (8.5%)	Silver carp (2.5%)	Carpio (17%)	Silver barb (52%)	Grass carp (4.3%)
Uzanishar	Rui (9%)	Catla (6%)	Mrigal (9%)	Silver carp (2%)	Carpio (18%)	Silver barb (2%)	Grass carp (4%)
Narail							
Sadhukhali	Rui (10%)	Mrigal (7%)	Carpio (28%)	Silver barb (55%)	–	–	–
Maizpara	Rui (10%)	Mrigal (7%)	Carpio (28%)	Silver barb (55%)	–	–	–
Muktagacha							
Halida	Rui (8%)	Catla (8%)	Mrigal (8%)	Silver carp (2%)	Carpio (24%)	Silver barb (42%)	GIFT (8%)
Kuripara	Rui (10%)	–	Mrigal (10%)		Carpio (23%)	Silver barb (47%)	GIFT (10%)

repairing, and water management and watched the field at night to prevent poaching.

Harvesting of fish. At all sites, fish harvesting started during the last week of December in each year, first with repeated seine netting and later by drying out the rice fields. The length, weight, and number of the fish were recorded. Production and survival were estimated.

Results and discussion

The production performance of the different sites in the last three consecutive years is presented in Tables 7, 8, and 9. In 1998, the range of production of the different sites was 75 to 528.6 kg ha^{-1}, with the highest production achieved at Kuliarchar (528.6 kg ha^{-1}) and the lowest at Narail (75 kg ha^{-1}, Table 7). The survival rate of fish at the different sites was very low and ranged from 4.9% to 16.2% only. In 1998, all the experimental sites were affected by devastating flood. The survival rate recorded was very low because of escaping fish during the flooding period. In 1999, comparatively higher production was achieved at all the experimental sites. The production of Kuliarchar, Barahambaria, and Narail sites was 508.2–544.5, 398.0–817.0, and 154 kg ha^{-1}, respectively (Table 8). The highest production (817 kg ha^{-1}) was obtained in Uzanishar, Barahambaria, whereas the lowest production (154 kg ha^{-1}) was at Narail. The survival rate was higher at all the sites in 1999 than in 1998, though in 1998 the project was affected by flash flood. Survival rates of 31.9–42.4%, 23.6–59.9%, and 19.0% were obtained at Kuliarchar, Barahambaria, and Narail, respectively.

In 2000-01, the harvesting of fish at all the experimental sites was not yet completed. The estimated production was calculated on the basis of the last sampling weight, which was calculated at the end of November. The estimated production performance of all the experimental sites was fairly high in comparison with the last two years (1998 and 1999). Among the sites, the highest estimated production was obtained by Barahambaria and Narail, which was 1,602–1,956 and 1,229–1,795 kg ha^{-1} in the 5-month culture period (Table 9). For Kuliarchar and Muktagacha, the estimated production was 545–1,152 and 426–850 kg ha^{-1}, respectively, in the 5-month rearing period. It is evident from the fish sampling data that the lowest growth performance took place at the Halida site in the Muktagacha area. At this site, the water was very turbid and its transparency varied from 5 to 12 cm. Because of this phenomenon, the individual growth rate was very poor. For this reason, production was very low in comparison with the other sites. The water quality parameters of various sites are presented in Table 10. The mean water temperature (°C), water depth (m), pH, and mean transparency (cm) were 28.70 ± 0.77 to 30.98 ± 2.12, 0.40 ± 0.07 to 2.00 ± 0.78, 6.0–8.8, and 10.78 ± 6.70 to 44.64 ± 32.70 at the different sites. Dissolved oxygen was determined only at the Muktagacha site, where the range of dissolved oxygen was 3.2–5.76 mg L^{-1}.

The production obtained in 1998 and 1999 was not encouraging because of the drastic flood that flushed away most of the stocked fish from the project sites; only a small number of fish were recovered. In 2000, however, the fish harvesting, though not yet completed, showed a highly promising estimated production at different sites.

Table 7. Stocking density, production, and survival of fish under the deepwater rice-fish productivity project during 1998.

Site name	Area of rice field (ha)	Stocking density ha^{-1}	Culture period (mo)	Site-wise production (kg ha^{-1})	Production (kg ha^{-1})	Survival (%)
Kuliarchar						
Monoharpur	2.2	13,000	6	1,163	528.6	16.2
Bagpara	8.4	11,000	6	3,516	418.6	6.7
Barahambaria Baria	3.8	6,500	6	1,650	434.2	6.7
Narail	3.6	5,000	5	270	75.0	4.9

Table 8. Production and survival of fish under the deepwater rice-fish productivity project at different sites during 1999.

Site name	Area of rice field (ha)	Culture period (mo)	Site-wise production (kg)			Production (kg ha^{-1})	Survival (%)
			Cultured fish	Wild fish	Total		
Kuliarchar							
Monoharpur	2.2	6	893	225	1,118	508.2	31.9
Charkalampur	2.8	6	1,361	180	1,541	544.5	42.5
Barahambaria Baria							
Urshiura	6.1	6	2,156	260	2,416	398.0	23.6
Uzanishar	42.1	6	632,926	1,480	34,400	817.0	59.9
Narail							
Sadhukhali	7.7	6	924	240	1,182	154.0	19.0

Table 9. Production and survival of fish under the deepwater rice-fish productivity project at different sites during 2000.

Site name	Area of rice field (ha)	Stocking density ha^{-1}	Culture period (mo, up to November)	Site-wise estimated production (kg ha^{-1})	Estimated production (kg ha^{-1})
Kuliarchar					
Konapara	1.8	6,800	5	2,073	1,152
Agarpur	6.0	5,300	5	3,264	545
Barahambaria Baria					
Urshiura	7.2	5,750	5	11,532	1,602
Uzanishar	40.0	5,750	5	78,234	1,956
Narail					
Sadhukhali	7.6	5,500	5	13,640	1,795
Maizpara	6.0	6,000	5	7,372	1,229
Muktagacha					
Halida	4.0	5,875	5	1,702	426
Kuripara	1.4	5,250	5	1,190	850

Table 10. Mean water quality parameters of different sites of the deepwater flood-prone ecosystem.

Parameter	Kuliarchar		Barahambaria Baria		Narail		Muktagacha	
	Konapara	Agarpur	Uzanishar	Urshiura	Sadhukhali	Maizapara	Halida	Kuripra
Mean water temperature (°C)	30.83 ± 1.65	30.27 ± 1.64	30.63 ± 2.00	30.98 ± 2.12	30.68 ± 01.70	30.48 ± 01.61	28.70 ± 0.77	28.78 ± 0.96
Mean water depth (m)	1.23 ± 0.40	0.92 ± 0.37	2.00 ± 0.78	1.38 ± 0.60	1.13 ± 00.54	1.16 ± 00.61	1.06 ± 0.18	0.40 ± 0.07
pH	7.5–8.1	7.2–8.6	7.7–8.9	7.6–9.0	7.2–8.8	7.1–8.7	6.0–7.3	6.0–7.3
Mean transparency (cm)	29.44 ± 2.89	30.45 ± 9.70	35.50 ± 11.51	41.6 ± 10.44	44.64 ± 32.74	3.70 ± 25.70	10.78 ± 11.70	4.13 ± 5.80
Mean dissolved oxygen (mg^{-1})	–	–	–	–	–	–	4.10 ± 0.67	4.47 ± 0.72

Hossain et al (1987) reported fish production of 43.2 to 146.30 kg ha^{-1} when *Lobia rohita*, *Ceprinus catal*, *C. reba*, *C. carpio*, and *Barbodes gonionotus* were cultured in various combinations. Kohinoor et al (1993) reported initial on-farm trials with *B. gonionotus* stocked at 3,000 ha^{-1} over a growing period of 70–90 days. Gross production of fish reached 58–104 kg ha^{-1}. Studies were undertaken in deepwater rice at Tangail using 4-m-high net enclosures, which showed fish production as high as 650 kg ha^{-1} in 4 months with supplementary feeding. Fish production was much higher than in more conventional rice-fish farming (Ali et al 1993, Gupta 1998).

In concurrent rice-fish culture management, rice yield was higher than in rice cultivation alone. So, in concurrent fish-rice culture management, the effect on rice production was positive and, at the same time, an additional fish crop was obtained (Kohinoor et al 1993).

On the basis of the last three years of experience, the following constraints can be summed up:

- **Social conflict**

Farmers could not be unified to undertake fish culture in rice fields of the deepwater flood-prone ecosystem. Social conflict can be solved by forming a cooperative society in which landowners will be members.

- **Lack of technical know-how**

Farmers lack knowledge of integrated rice-fish farming. Extension efforts should be strengthened to disseminate the technology.

- **Nonavailability of fish fingerlings**

During stocking, the required size (6.0–8.0 cm) of carp fish fingerlings was not available. For the availability of these fingerlings during stocking, a trusted nurserer should be selected 6 months before who can supply the fingerlings at a reasonable price.

- **Capital**

The cost was comparatively less for fish culture in rice fields but, because of poor socioeconomic conditions of farmers in Bangladesh, capital may not be available during the stocking of fingerlings, for bamboo fences, and for other managerial work. Commercial banks such as the Bangladesh Krishi Bank, Sonali Bank, Agrani Bank, and Janata Bank and nongovernment organizations will provide necessary funds for farmers as credit.

- **Flood**

Flash flooding is one of the major problems affecting fish culture in the deepwater rice ecosystem. During heavy rains, plots become flooded and fish escape from one field to another. Increasing dike and fence height to protect fish from heavy rains and flooding is needed.

- **Poaching**

Poaching is a critical problem in all sorts of fish culture in Bangladesh. Vigilant watching could protect the fish from poaching.

- **Predatory fish and aquatic animals**

The rice field is a suitable environment for predatory fish and aquatic animals. During stocking, they could prey on the fish and reduce the survival rate of desirable fish.

- **Possible destruction of rice seedlings by herbivorous fish**

In concurrent management, if stocking could be done before transplanting of rice seedlings, herbivorous fish such as silver barb (*Barbodes gonionotus*) might uproot the rice seedlings. At the Muktagacha site, this phenomenon was observed. But, at the Narail site, farmers stocked the fish 3 weeks after rice seedling transplantation and this phenomenon was not observed as at the Muktagacha site. So, fingerlings should be stocked in the rice fields 3 weeks after transplanting of rice seedlings.

There are many areas of Bangladesh where fish-rice culture in flood-prone ecosystems could be adopted. In these areas, water is retained for 4–6 months during the rainy season and, in most cases, rice cultivation would not be possible because of flash flooding. But, these vast water bodies or rice canopies are used as natural habitats for wild fish such as catfish, climbing perch, snakehead, eel, and even prawn (Das et al 1990). The yearly silt deposition and organic matter decomposition could enhance the growth of naturally occurring phytoplankton, zooplankton, periphyton, and benthic organisms. If these water bodies can be used for fish culture with some management, this will lead to an increase in fish production as well as helping with nutritional requirements. The possible areas of fish-rice culture under such environments are as follows:

- The Jamuna floodplain, which is located in the districts of Netrokona and Tangail.
- The Ganges floodplain, which is represented in the districts of Rajshahi and Sirajgong.
- The Surma/Meghna floodplain, which is located in the greater district of Comilla.
- The tidal floodplain, which is represented in the districts of Greater Khulna, Jessore, and Barishal.

Conclusions

Deepwater fish-rice farming in flood-prone environments is an ideal way of integrating aquaculture and agriculture to maximize production from both water and land areas. It offers one of the best opportunities to involve farmers in producing additional work, income, and nutrition.

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Rice biodiversity and gentic improvement

Rice biodiversity and genetic wealth of the flood-prone environment in eastern India

R.K. Singh, J.L. Dwivedi, R. Thakur, S. Mallik, and T. Ahmed

More than 2.3 million ha of rice area in eastern India are flood-prone. The rice in flood-prone areas suffers from unpredictable floods and occasional drought. Because of the varying eco-cultural conditions, farmers grow different rice varieties suiting their local conditions. These areas therefore harbor large varietal diversity. Because of the lack of appropriate varieties, the loss from genetic erosion has been much less in flood-prone areas than in other ecosystems. Institutions in eastern India have collected more than 1,000 accessions, many of which have been screened and evaluated. There is a need to evaluate (also at the molecular level) and properly document the available germplasm at different centers and information needs to be made available freely to breeders throughout the region. Further collections are also needed from the unexplored remote areas. Some suitable donors for various biotic and abiotic stress-related traits have been identified and are being used in breeding programs. As a result, some improved varieties with better performance and resistance were developed, although most of these varieties are limited in adaptation to varying on-farm conditions. There is a need to develop more varieties suitable for local needs for early on-farm testing, rather than a few varieties with more traits combined in them.

With more than 42 million hectares of rice area, India is the largest rice-growing country in the world. However, only 45% of this area is irrigated. Of the remaining 55%, 33% is rainfed lowland, 15% rainfed upland, and 7% flood-prone. The major flood-prone areas are in eastern India—eastern Uttar Pradesh, Bihar, West Bengal, Orissa, and Assam (Table 1). Flooding occurs during the wet-season months of June-October. Most crucial for rice plants are the age of the plants at the time of inundation, the rate of water rise, and the duration of flood. Soils are fertile but some adverse soils such as acid-sulfate and saline soils also occur. Because of the variation in flooding pattern coupled with the array of maturity time needed, varieties grown in different provinces are not the same; different varieties are adapted to different environmental situations. Unlike in other ecosystems, a full range of varieties, from primitive to improved types, are under cultivation in the flood-prone ecosystem.

Rice biodiversity refers to the varietal diversity in rice in farmers' fields. It has both a temporal and spatial connotation. This diversity provides the base for rice

Table 1. Extent of flood-prone rice area in eastern India.

State	Area (000 ha)
Bihar	830
Assam	493
West Bengal	463
Uttar Pradesh	390
Orissa	121
Tripura	34
Manipur	20
Mizoram	4
Total	2,355

improvement either through pure-line selection or by involving these cultivars in hybridization as parents. FR13A, the best known submergence-tolerant variety, is the shining example of a pure-line selection from Dhula-Puttia, a locally grown landrace. Similarly, Purnendu and Barh Avarodhi varieties from West Bengal and Uttar Pradesh, respectively, provide excellent examples of how proper selection and use of germplasm in a hybridization program can produce miraculous results. Biodiversity maintained *in situ* or conserved *ex situ* is a treasure that humanity should respect and do all that is required to save it from becoming extinct. However, the loss of biodiversity (genetic erosion) is taking place at a rate that threatens the very survival of humankind. In India, a good example is the fast erosion of aromatic rice cultivars and landraces (Singh and Singh 1998). Because, in the past, emphasis has been mainly on increasing yield, the release and spread of high-yielding varieties have caused the fast replacement of low-yielding locally grown scented rice cultivars. For various reasons, the replacement of cultivars in flood-prone areas has been negligible. This paper deals with the complex flood-prone rice environment of eastern India and the large rice genetic diversity that it harbors, offering scope for future flood-prone rice improvement.

Flood and associated rice types in eastern India

Of the total of 2.3 million ha of flood-prone rice lands in eastern India, eastern Uttar Pradesh alone has 0.39 million ha. These areas are located in the depressed basin and low-lying areas adjacent to rivers in different districts—Basti, Mahraj Ganj, Gorakh Pur, Deoria, Ballia, Gazipur, Varanasi, Gonda, Faizabad, Barabanki, and Bahraich—and are subject to various types of uncontrolled flooding ranging from 50 to 400 cm. Four major rice cultural types are grown in the flood-prone ecosystem: (1) submergence-tolerant, (2) stagnant deep, (3) floating, and (4) boro rice. The types of rice and occurrence of flooding patterns are described below.

- *Flash flood/temporary submergence.* Crops are submerged for a short duration because of heavy monsoon rain. Such areas are located in Barabanki, Bahraich, Gonda, Basti, Vanarasi, Gorakhpur, Sant Kabir Nagar, and Kushinagar districts. About 200,000 ha are submerged for a short period annually. Barh Avarodhi and Madhukhar varieties are adapted because of their survival ability under complete submergence for 7–10 days. Data collected from 1997 to 2000 on the flash-flood situation at the Crop Research Station in Ghaghraghat, Uttar Pradesh, India, show wide variability within seasons and between years (Table 2).

- *Deep stagnant (50–100 cm).* Stagnant flooding is associated with deepwater rice where water stagnates in the field for at least 30 days during the crop season. About 140,000 ha of deepwater rice are grown on the floodplains of major rivers in Deoria, Gorakhpur, Basti, Sant Kabir Nagar, Ballia, and Bahraich districts. Floodwater commonly rises at 2–3 cm per day depending on the rainfall coupled with river flows. Chakia 59 and Jalpriya are improved varieties grown mostly in this situation. These varieties are photoperiod-sensitive, flower in the 3rd week of October, and mature in 140–170 days.
- *Very deep stagnant (>1 m water depth).* About 50,000 ha of land are flooded from 1 to 3 m annually in eastern Uttar Pradesh. Floating rice is grown in this situation. Such rice possesses the ability to elongate under submergence, around 5 cm per day, to maintain its foliage above the floodwater. Major floating rice areas are in Ballia, Sant Kabir Nagar, Deoria, Gorakhpur, and Bahraich districts. Floating rice is seeded in dry conditions in April before the onset of the monsoon. Once the water enters the field, it stagnates for the next 3–4 months. The water gradually recedes even up to December. Besides the traditional varieties, Jalnidhi and Jalmagna are common in such deeply flooded areas.
- *Off-season deep stagnant*. Rice grown in the flood-prone ecosystem during the dry season is called boro. Boro rice is cultivated in Ballia, Gorakhpur, Deoria, Maharaj Ganj, Siddharth Nagar, Basti, and Gazipur districts during the dry season, especially in local land depressions where there is sufficient residual moisture in the soil for raising the crop. The reported area under this situation is about 4,000 ha. Traditional boro rice still dominates in the areas with limited improved types. Poor adoption of high-yielding varieties may be ascribed to their lack of cold tolerance and low adaptability. Besides traditional boro rice, Saket 4, Jaya, Gautam, Pusa 2-21, Krishna Hamsa, Sarju 52, and Pant Dhan 4 are being grown in the boro season. Gautam, a recently developed variety from Rajendra Agricultural University, Pusa (Bihar), and Chinsurah Hybrid 1 from West Bengal have a yield potential of 5 to 6 t ha^{-1}.

The low-lying areas where water stagnates for a longer period are called *chaurs* (saucer-shaped land depression) or *maan/dhar* (abandoned river beds) in Bihar (Thakur et al 1998). They are scattered all over north Bihar and to some extent in the Central Gangetic Plain. A typical chaur has a high depth of water in the center and is shallow at the periphery, while maan/dhar are long strips and may be found in chains. Three

Table 2. Flood spells during 1990 to 2000 at the Crop Research Station, Ghaghraghat, Uttar Pradesh, India.

Year	Water inception date	Flood duration (d)	Peak water depth (cm)
1990	10 Jul	15	95
	28 Jul	6	68
	9 Aug	16	97
	28 Aug	2	31
	4 Sep	6	58
1991	5 Aug	2	27
	10 Aug	4	37
	18 Aug	6	35
	7 Sep	3	31
	10 Sep	3	40
1992	8 Aug	3	19
	20 Aug	3	19
	24 Aug	9	51
1993	8 Aug	6	16
	2 Sep	20	60
1994	11 Aug	10	45
	25 Aug	8	38
1995	2 Aug	6	18
	14 Aug	11	82
	30 Aug	16	96
1996	12 Jul	6	18
	21 Jul	5	38
	3 Aug	3	15
	7 Aug	21	75
	1 Sep	13	64
1997	11 Jul	2	27
	27 Jul	3	22
	2 Aug	7	60
	11 Aug	9	80
	21 Aug	3	35
	8 Sep	9	50
1998	7 Jul	5	23
	18 Jul	15	78
	3 Aug	35	134
1999	27 Jul	5	23
	13 Aug	5	36
	30 Sep	6	40
	8 Oct	3	45
2000	8 June	4	35
	22 June	3	36
	2 Jul	3	11
	8 Jul	3	21
	12 Jul	14	36
	29 Jul	10	70
	8 Aug	2	30
	11 Aug	12	72
	30 Aug	15	36

Source: Crop Research Station, Ghaghraghat, Uttar Pradesh, India.

types of chaur are identified: (1) medium deepwater, where water depth remains around 1 m, which overlaps with chaur where rainfed lowland rice is grown. In such conditions, tall, early photosensitive cultivars are grown, which have a limited elongation rate and survive by their tall stature; (2) deepwater, where water depth goes up to 1 to 2 m, where tall, medium-late aman (photosensitive) cultivars are grown having varying degrees of leaf elongation with good kneeing ability; and (3) very deepwater, with depth up to 2.5 to 3 m, where late aman (photosensitive cultures) with a high rate of elongation are grown by broadcasting (Thakur 1985).

In Assam, flood-prone rice is classified as *asra* and *bao* types. Asra is an ecotypic group of *Sali* rice adapted to shallow water and semideepwater conditions (up to 1 m water depth). The cultivars of this group are tall, thick-culmed, leafy, coarse-grained, and nonscented. However, variability exists for the characteristics associated with adaptability to field water levels and tolerance for submergence. Bao varieties are adapted to deepwater (1 to 4 m) and have tall stature, floating habit, nonscented coarse grains, a high rate of elongation, and kneeing ability.

Of the total of 0.46 million ha of flood-prone rice lands in West Bengal, about 70% suffer annually with 50–70-cm water depth. At present, the rice varietal improvement program for flood-prone areas is in operation at the Regional Rice Research Station, Chinsurah and Canning centers. Part of the coastal areas have soil problems, especially salinity and Zn deficiency.

In Orissa, a majority of the area is in the category of intermittent/flash flooding and coastal areas with problem soils. The Research Station in Ranital, Bhubaneswar, and Central Rice Research Institute, Cuttack, are now engaged in improving flood-prone rice.

Biodiversity and genetic wealth in the flood-prone ecosystem

The genetic wealth of cultivated and wild rice germplasm in eastern India is rich and diverse. This remarkable diversity is explained by various water regimes/topography; soil types; required variation in plant stature, flowering time, and growing period; photoperiod sensitivity (mild to strong); and requirements of local farmers. Small differences in topography greatly affect flooding and the cropping system. Because of the extremely diversified agroecological system, it is obviously not feasible for a single genotype to perform consistently well in different environments. Accordingly, certain competing traits—submergence in flash flooding, elongation ability in stagnant deepwater and floating rice, and cold tolerance in boro rice—are involved for adaptation. In addition, photoperiod sensitivity makes rice fit into a specific pattern. It allows the crop to flower at the right time even if farmers sow the crop early or late (Dwivedi et al 2000). The relationships among flowering date, growing period, and water regime appear in Table 3.

Table 3. Growing period and flowering time of improved flood-prone rice varieties adapted to different water regimes.

Ecological situation	Cultural type	Improved varieties	Growing period	Flowering time
Deepwater/floating (>100 cm water depth)	Direct-seeded/ transplanted	Jalmagna, Jalnidhi, Padmanath, Purunendu, Sudha, Panindra, Jitendra	Mar-Dec	1st week of Nov
Off-season deep stagnant	Boro rice	Gautam, Jaimati, Saket, Prabhat, Bishnuprasad, Biplab, Joyti, IR36, IET4094, Lalat, and Chinsurah hybrid 3	Nov-May	Apr
Semideepwater 50–100 cm)	Transplanted	Chakia 59, Jalpriya, Panidhan, Sabita, Dinesh, Amulya, Panidhan, Sudhir, Mandira	Jun-Nov	3rd week of Oct
Medium deep (30–50 cm)	Transplanted	Jal Lahari, Mahsuri, Manohar Sali, Matangani, Nalini	Jun to 15 Nov	2nd week of Oct
Flash flood	Transplanted/ direct-seeded	Tulasi, Barh Avarodhi, Madhukar, JM50, Maguri bao	Jul-Nov	3rd week of Oct
	Direct-seeded	Kopilee, Neela, Luit, Kalinga III Dec	Late Aug-Oct	2nd week of

Collection, evaluation, and use of germplasm

Among notable rice collections, including flood-prone rice, are the Jeypore Botanical Survey, which led to the collection of 1,745 cultivars from south Orissa and adjoining areas of Madhya Pradesh; the Assam Rice Collection during 1965-72, which added 6,630 accessions; joint explorations of the National Bureau of Plant Genetic Resources and State Agricultural Universities (1978-80) and CRRI (1995), resulting in the collection of about 7,447 accessions from Sikkim, south Bihar, and parts of Orissa; and 6,630 accessions collected under PL480. Screening of these materials has yielded some excellent donors for breeding programs. Currently, the Assam Agricultural University (AAU) maintains a collection of 250 asra-type germplasm accessions at its Karimganj Rice Research Station and 62 bao-type cultures at RRS Titabar.

Various research institutions in eastern India have collected flood-prone rice. Most important among them are the Crop Research Station, Ghaghraghat, in Uttar Pradesh; Rajendra Agricultural University, Pusa, in Bihar; RRS Chinsurah, in West Bengal; CRRI, Cuttack; and AAU, Jorhat, Assam. The current status of flood-prone rice accessions in national gene banks and their estimated numbers appear in Table 4. Flood-prone rice research in Uttar Pradesh dates back to the early 1960s with the

Table 4. Current status of indigenous flood-prone rice germplasm in eastern India.

Province/state	National gene bank		Reference
	Actual numbers	Estimated numbers	
Assam			
Asra	274	1,000	Singh et al (2000)
Bao	62		
West Bengal	>100	200	Catling (1992)
Bihar	300	300	Catling (1992)
Uttar Pradesh			
Indigenous	85	100	Dwivedi (2000)
Exotic	229	–	
Others		200	

establishment of the Flood-Prone Rice Research Station, now called the Crop Research Station, Ghagharaghat, in Bahraich District. Soon after the establishment of the center, efforts were made to collect local rice from flood-prone areas. Several landraces and wild rice species were collected from different water regimes and subecosystem conditions. Since then, local and exotic germplasm related to flash flood, stagnant deep, and semideepwater situations is being collected and maintained. Up to now, 293 accessions including landraces and exotic varieties are being maintained at the Crop Research Station, Ghaghraghat, Bahraich, and are in the final stage of evaluation and documentation. These accessions are being evaluated for 36 vegetative, morphological, reproductive, and maturity traits. Major emphasis was given to adaptability traits. Results revealed that varieties grown in stagnant deep flooding did not possess submergence tolerance. Nondestructive screening techniques for elongation ability (Dwivedi et al 1992) and the genetics of elongation ability and submergence tolerance involving this germplasm have been studied (Dwivedi and Senadhira 1993, 1994). Jalmagna, Jalnidhi, and *Oryza rufipogon* possess excellent elongation ability, Madhukar and Barh Avarodhi have a high degree of flood tolerance, and Jalpriya has better grain quality. In addition, wild rice is a good source of donors for abiotic and biotic stresses.

It is believed that 15–20% of the landraces have not yet been collected from deepwater and flood-prone areas that are located in remote places and are accessible only by boat (Dwivedi 1996).

During the 1920s and 1930s, 250 genotypes were collected from north Bihar and 5,000 from all over Bihar and Orissa by Alam (1937). These also included deepwater genotypes. Later on, three collections, based on evaluation under deepwater conditions, were recommended for general cultivation (Verma and Saran 1974). Under the Ford Foundation-supported project (1977-80), the entire north Bihar was surveyed and 260 local landraces of rainfed lowland and 90 deepwater landraces were collected. They were all tall except for three intermediate types: TCA20-1, TCA20-2, and TCA217 (Singh 1982, Thakur 1985). Saran et al (1996) have collected and described important features of landraces of the North and Central Gangetic Plains of Bihar.

The elongation rate of selected cultivars has been ascertained (Thakur and Singh 1983, Khan et al 1987). TCA177 showed an elongation rate as high as 23 cm day^{-1}. The rate decreases with the period of submergence (Khan et al 1987). Cultivars have also been evaluated systematically for several morphological traits (Verma 1991). Many of them, as shown below, have been found to be good donors for resistance to various diseases and pests (Thakur et al 1981): for rice tungro virus: 190-1, TCA72, and TCA177; for bacterial leaf blight: TCA4, TCA177, TCA212, and TCA214.

These collections have also been screened for physiological efficiency at Narendra Development University of Agriculture and Technology (NDUAT), Faizabad, and TCA48 and TCA85 were found to be highly tolerant of submergence.

In West Bengal, the choice of variety for the flood-prone environment was very meager before the 1980s. Jaladhi 1 and Jaladhi 2 and some traditional varieties such as Meghi, Sadamota, Achra, Kumargone, and Panikalash were the only choices for this ecosystem. All the varieties have short, bold grains with red kernel. Systematic efforts were intensified during the early 1980s to develop superior varieties for the ecosystem.

As a first step, germplasm was collected from different parts of the state. There are now 500 germplasm accessions. Germplasm was also collected from other states. We can mention Begunia Khazara and Dhusara, collected from Orissa. Materials received from INGER nurseries and the plant breeding division of IRRI enriched the germplasm collection. For example, during the wet season of 2000, IR60608 and IR64588, both having *O. rufipogon* as one of the parents, were evaluated.

Five tolerant varieties (FR13A, FR43B, and three somaclonal variants of FR13A), two susceptible varieties (IR42 and Mahsuri), two varieties for the shallow situation (Jogen and Suresh), two semideepwater varieties (Sabita and Jitendra), and two deepwater varieties (Jaladhi 1 and Purnendu) were screened for flood tolerance. In single submergence, when the plants were submerged at 110 days after sowing (DAS), all the varieties could survive, but, at 50 DAS, three varieties, Jaladhi 1, Mahsuri, and IR42, could not survive at all. When the same genotypes were submerged at two growth stages (50 + 80 DAS) repeatedly, only five varieties, FR13A, FR43B, and three somaclonal variants of FR13A, could survive. In repeated submergence at three stages (50 + 80 + 110 DAS), only the somaclonal variants survived. So, where submergence occurs repeatedly, such genotypes may be useful donors.

Keeping in view the requirements, germplasm screening was done to identify donors for various traits (Table 5). These are being used in a hybridization program to develop appropriate varieties in India and elsewhere. Evaluation of submergence-tolerant and elongating lines from IRRI and Thailand resulted in the identification of acceptable and adaptable lines. This was evident from the results obtained at the Crop Research Station, Ghaghraghat, Uttar Pradesh (Table 6).

India is also rich in genetic diversity of wild *Oryza* species, particularly *O. nivara, O. rufipogon, O. officinalis, O. spontanea, O. ridleyi,* and *O. perennis*. Re-

Table 5. Suitable deepwater rice varieties identified and used as donors.

Character	Donors
Elongation ability	Baisbish, Jalmagna, Negharibao, LMN 111, TCA 177, Padmapani, *Oryza rufipogon,* Jalnidhi
Submergence tolerance	FR13A, FR13B, BKNFR 76106-16-0-1, IR31432-6-2-2-3, IR31406-33-1, IR28884-26-3-505-1-1, Madhukar, Kekowabao, Nagheribao, Dhunsara, Begunia, Khazara, Maguribao, Barh Avarodhi, Kurkaruppan, Godhahinati
Drought tolerance	RD 19, Patnai-23, CR 1009, NC 1626, Baisbish, BIET 821, Gurmatia
Photoperiod sensitivity	CNW 539, CN 505-5-32-9, Janki, TCA 48, Jalmagna, BIET 821, Safri 17
Seed dormancy	CN 499-160-13-6, FR13A, Sabita
Long panicle	OR 143-7, BIET 807, TCA 4, FRG 7, Kalimooch 64
Ufra resistance	Rayada 16-06, Rayada 16-09, Rayada B3, Bazail 65, Ufra 4, Ufra 12, Ufra 14, Ufra 15, Ufra 16, *O. rufipogon*, Padmapani
Kneeing ability	Nagheribao, Balbao, Amonabao, Padmapani, ARC 5955, Bankura, Kania, Bhaluchala, Ravana, Jalmagna, Jalnidhi, NDGR 417, NDUR 21
P and Zn deficiency and salinity	Damodar, Dasal, Cherivi ruppu, Pokali, SR 26B, Kalarata 24, Patnai 23, IR55008
Alkalinity	Jalmagna, Madhukar
Grain quality	CR 1014, KDML 105, Mahsuri, and IRRI improved lines
Iron toxicity	Samahe, Mahsuri

Table 6. Submergence-tolerant and elongating lines from IRRI and Thailand tested at Ghaghraghat, Uttar Pradesh, during 1993-96.

Source	Particular	1993	1994	1995	1996
IRRI	Submergence-tolerant lines	62 (19)[a]	30 (15)	22 (9)	100 (0)
	Elongating lines	63 (18)	38 (8)	77 (31)	100 (30)
Thailand	Breeding materials	36 (3)	114 (0)	42 (21)	82 (71)

[a] In parentheses are the number of lines selected.
Source: Crop Research Station, Ghaghraghat, Uttar Pradesh, India.

cently, variability in *Porteresia coarctata* has been reported from the coastal areas of eastern India.

High pest incidence and coevolution of rice pests of wild rice suggest that a wild rice population collected may be a valuable source of pest and disease resistance, besides resistance to abiotic stresses. *O. nivara*, a wild rice, is the only source of resistance to grassy stunt virus. *O. rufipogon* is perennial and photoperiod-sensitive, with thick and long culm and well exserted and spreading panicles, and it possesses the ability to elongate fast under abrupt flooding.

Table 7. Leading improved and traditional flood-prone rice cultivars of eastern India.

State	Adaptability	
	Deepwater (50–100 cm)	Floating (>100 cm)
Assam		
Recommended Herepi, Jaldhan 1	Bir Pak, Sail Badal, Pani Kekua, Badal, Kekua Bao	Aiki Bao, Amona Bao, Dhola
Traditional/ others	Ikarasali, Lati Sali, Mahsuri, Manohar Sali, Ogri Sali, Pankaj, Sialasali	Kalangi Bao, Maguri, Moimorsingia Bao, Neghari Bao, Ranga Bao
West Bengal		
Recommended	Achra 108-1, Mandira, Jogan, Mahsuri, Sabit, Kumargore, Patnai 23,Tilaka Chari, Jitendra, Dinesh, Jalprabha, Baghirathi, Ambika	Jaladhi-1, Jaladhi-2, Saraswati, Hamseshwati, Purnendu, Jalprabha
Traditional	Agriban, Bhasamarik, Gochi, Kalma, Meghi	Digha, Ogar, Khalirai
Bihar		
Recommended	BR 14, BR 46, Jaladhi-1, Janaki, Sudha	BR 14, BR 46, TCA 4, Varidhi
Traditional	Bakol, Dasmi, Jogar, Kalma, Salmot, Sugara	Barogar, Desaria, Maghnath, Jessoria group, Sohar Desaria
Uttar Pradesh		
Recommended	Chakia 59, Madhukar, Barh Avarodhi, Jalpriya, Cross 116	Japmagna, Jalnidhi, NDUR 417, NDUR 421
Traditional	Sainger, Agahari, Gauria, Aamgaud, Venaga, Dhaneshwar	Goanth, Balgani, Kabara, Balmlot, Sugaparkhi, Ghoghari

Loss of genetic biodiversity

There is little genetic erosion in flood-prone rice in eastern India owing to the release of only a few high-yielding varieties in this ecosystem (Singh et al 2000). The rate of replacement of landraces is slow because of the poor seed distribution system and farmers' preference for specific traits. The leading flood-prone rice cultivars grown in eastern India (Table 7) clearly indicate that traditional varieties still have a substantial share in the area. A recent survey carried out in flood-prone areas indicated that a good number of traditional varieties—including Malhi, Suapankhi, Amgaud, Kajari Lalha, Venaga, Agahani, Gauria, and Dhanesar in flash flood; Barogar, Cross116, and Saingar in deep stagnant water; and Jaisuria, Sugapankhi, Bainaslot, Goanth, Ghoghari, and Tairaki in floating rice areas—are still cultivated, besides the improved types.

A review of the varietal diversity in farmers' fields clearly indicates that the traditional varieties grown in uplands earlier have more or less been replaced by the modern varieties. This was particularly so in the areas that had better access and

Table 8. An estimate of varieties lost in different ecosystems.

Ecosystem	% varieties lost
Upland	60–70
Rainfed lowland (favorable)	70–80
Rainfed lowland (unfavorable)	20–30
Flood-prone	<5

Table 9. Number of rice varieties grown by farmers in different selected villages (1998) of eastern Uttar Pradesh.

No. of varieties grown by each farmer	Basalatpur	Sariyawan (%)	Mungeshpur
1	18	52	36
2	44	28	32
3	24	18	16
4	8	2	14
5	4	–	2
6	2	–	–
Total	100	100	100

resources than the inaccessible and remote areas. The replacement of traditional varieties has been comparatively low in rainfed lowland and more so in flood-prone deepwater areas. However, in the favorable rainfed lowland, modern varieties have already started having an impact. Where farmers have adopted modern varieties, they have carefully chosen fields that provide favorable environments and also managed the crop better. Although the high-yielding modern varieties have had little impact in flood-prone deepwater areas, diversity in such areas is being lost mainly because of the changing cropping patterns. Table 8 contains an estimate of varieties lost in different ecosystems. The rice crop in the deepwater area in some places is being replaced by a boro-season rice crop that assures high yields and profitability to farmers (Thakur and Singh 2000).

In a study on the diversity of varieties grown by farmers in some villages in Orissa, researchers found that the sampled farmers grew as many as 30 traditional and 11 improved varieties. Farmers almost invariably grew more than one rice variety on their farms with the number of varieties ranging from two to more than 10. More than 70% of the farmers grew two to five varieties, while 20% of the farmers grew six to eight varieties. NDUAT scientists made similar observations in eastern Uttar Pradesh (Table 9). The pattern further showed that in flood-prone areas such as two and three land forms in Orissa, and Basalatpur in eastern Uttar Pradesh, farmers grew a larger number of varieties than in the rest of the cases (Table 10). Farmers are

Table 10. Traditional and improved cultivars grown by farmers in some rainfed/flood-prone villages of eastern Uttar Pradesh.

Type of variety	No. of farmers and area (ha)					
	Basalatpur		Sariyawan		Mungeshpur	
	No.	Area	No.	Area	No.	Area
Traditional	44	24.75	21	4.31	14	2.53
Improved	30	23.42	43	19.47	48	18.42

selecting new varieties very carefully, keeping in view the land type, soil type, water regime during crop growth, and availability of life-saving irrigation water.

Production constraints and varietal needs in flood-prone areas

Semideep and deepwater areas suffer from a host of soil and water-related problems, besides pests and diseases. Poor crop establishment because of early drought and/or submergence, suppressed tillering because of prolonged waterlogging, crop damage caused by cycles of flash floods at different stages of crop growth, and nonavailability of varieties with flood/submergence tolerance are among the most important constraints to semideepwater flash-flood rice. In some areas, iron toxicity is also a major problem. In deepwater areas, the low plant population caused by extreme floods and droughts, heavy weed infestation, and poor crop management results in low yields. The lack of appropriate varieties adapted to deepwater areas is the major constraint to high yields. Yellow stem borer and ufra are among the most damaging insects and diseases, respectively, in deepwater rice.

Other constraints relate to land and soils such as extreme soil acidity, soil alkalinity, and salinity. N, P, and Zn deficiency are widespread. Most resource-poor farmers cannot afford the inputs necessary for maximum production.

Besides proper crop and resource management, the varietal requirement of the flood-prone area is a serious issue. Although the major concern in semideepwater flash-flood rice is submergence tolerance, moderate elongation ability for deepwater and very deepwater rice requires a fast elongation rate to cope with the rising water level, and kneeing ability to adjust to a drop in water level. For boro rice, cold tolerance of seedlings and seedling establishment are the main problems. Among other important traits are nodal tillering to compensate for poor plant population, drought tolerance at the early crop establishment stage, photoperiod sensitivity (flowering from the last week of October to early November), nonshattering behavior, and seed dormancy.

Conclusions

The genetic wealth of cultivated and wild rice in the flood-prone ecosystem is rich and diverse. Great varietal diversity among subecosystem types within an ecology may be ascribed to variation in flooding pattern, heterogeneous soil, maturity requirement, plant stature, and the specific demand of the local ecology and farmers' needs. Mutually exclusive choices in the articulation of breeding objectives must include a deepwater survival strategy and maturity timing starting from October to December. To cover the full range of prevailing diversity in the ecosystem, the development of more improved cultivars with desired characteristics and suited to local conditions will be the most appropriate strategy. This will make it possible to conserve biodiversity in such conditions and to meet farmers' requirements for enhancing productivity and production in the flood-prone rice ecology.

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Rice biodiversity and genetic wealth of flood-prone environments of Bangladesh

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Bangladesh is very rich in rice biodiversity by virtue of its wide variation in land, topography, and seasons. The rice genetic diversity of the flood-prone environment is widely distributed in the country. This genetic wealth of rice is threatened by the rapid spread of newly improved varieties as well as several devastating floods in the recent past. As a result, the germplasm of deepwater rice available in the country has been drastically reduced to about 60%. Though exploration and collection activities started after the British regime, there are still some pockets of inaccessible areas yet to be explored. About 700 deepwater rice cultivars were collected, for which 659 collections were catalogued and stored in the BRRI and IRRI gene banks. Before the gene banks were established, the collections were maintained as pure lines by growing them every year and characterized and classified into several groups. A total of 36 varieties were found to be moderately resistant to sheath blight (8), stem rot (1), bacterial blight (8), rice tungro virus (3), ufra (9), green leafhopper (1), brown planthopper (2), whitebacked planthopper (2), and stem borer (2). The nine best pure lines were released as varieties.

There are prospects for further collection of landraces as well as wild relatives. Immediate attention should be given to the collection and thorough study of the diverse deepwater rice varieties. Emphasis should also be given to evaluation, characterization, documentation, and use of the deepwater rice wealth in the country.

Bangladesh is a floodplain alluvium delta formed by the Ganges and Brahmaputra river system covering about 14.8 million ha of land area; out of this, 8.8 million ha are arable. About 5 million ha of land in this country become inundated, with a minimum of 30 cm up to a maximum of 300 cm annually (Catling 1992). The floods usually continue for 4–6 months and the water depth varies depending on topography and drainage facilities. The wide environmental diversity in Bangladesh, attributed mainly to the considerable variation in topographic and seasonal components, is reflected in the range of rice groups cultivated—aus, transplanted (T) aman, broadcast (B) aman, and boro—as well as in the distribution of wild and weedy species.

Biodiversity is the fundamental basis of evolution and plant improvement. Biodiversity provides a base for crop diversification. Monocropping is dangerous, risk-prone, and harmful to the environment. Biodiversity provides a mechanism of natural balance. A rich source of plant genetic resources (PGR) assures a successful crop improvement program for any nation (Zaman 1997).

Bangladesh is very rich in diverse tropical crop species by virtue of its location in a transitional point of the Indo-Burma gene center, within tropical and subtropical zones blessed by the monsoon climate. Moreover, the natural gene flow from Indian phyto-geographic regions of the Gangetic floodplains, eastern Himalayas, and north-eastern part have enriched our crop gene pool for a long time. The diversity of rice is very rich in this region. On the other hand, wild and weedy species are good gene sources of resistance to disease and insect pests and tolerance for stress environments, cytoplasmic sterility, adaptability to different growing conditions, high nutritional value, improved quality, etc. (Hawkes 1983). For instance, deepwater cultivars have outstanding ability for internode elongation within 4 weeks of seeding and other local rice cultivars are highly tolerant of flood submergence. Some cultivars have also provided the *Xa5* and *Xa7* genes for resistance to bacterial blight (cf. Lloyd and Jackson 1986). But this genetic wealth of rice is threatened by the rapid spread of newly improved varieties and by land clearing associated with irrigation and drainage projects. Even in the remote areas, indigenous varieties are disappearing at an alarming rate.

This paper will focus on the rice genetic wealth of the flood-prone environment during the pre- and post-Green Revolution periods. It will also indicate conservation measures and the best use of the wealth of the flood-prone environment in Bangladesh.

Origin of deepwater rice

It is generally accepted now that the center of origin of *Oryza. sativa* L. was Southeast Asia, particularly Bangladesh, eastern India, Burma, and Indochina, where the richest diversity of cultivated forms was recorded. The wide range of diversity of cultivars suggests a polyphyletic origin of *O. sativa*. Most authors believe that *O. rufipogon (O. fatua, O. sativa* var. *fatua)* was the progenitor of most of the varieties of *O. sativa*. The close similarity beween *O. sativa* and *O. glaberrima* and existence of intermediate forms suggest a monophyletic origin of *O. sativa.*

Deepwater varieties seem to have evolved from *O. rufipogon*, whereas the other nondeepwater forms are derivatives of the deepwater varieties. All the related wild species of rice have deepwater types and are grown wild in rice fields during the rainy seasons in Asia and Africa. Deepwater types are also found in the species of *O. glaberrima*. Thus, deepwater habit is a common phenomenon found in the related species of *O. sativa* and can be considered as a primitive character in cultivars (Choudhury 1974).

Three major groups can be distinguished within the deepwater rice cultivars of Bangladesh, as follows.

Group I. *Rayada.* These cultivars exhibit moderate flood resistance and are thus adapted to a shallow flood level of 1 to 1.5 m. They are endemic to the low-lying areas of the southwestern part of Faridpur, eastern part of Kushtia, and northeast part of Jessore District. The seedlings can grow in the cooler season and are thus cultivated mixed with the boro crop during the latter part of November. The seedlings grow along with the boro crop but the prevailing short day cannot induce flowering, which exhibits strict photosensitivity. As a result, Rayada plants continue to grow, whereas the boro crop flowers in April and is harvested in May. The Rayada plants usually flower in late September or in October when the daylength becomes shorter. The other vegetative and floral characters are similar to those of the usual deepwater cultivars but differ in a single character, that is, they do not show any seed dormancy, whereas typical deepwater rice has high seed dormancy.

Group II. *Deepwater rice.* These cultivars exhibit a varying degree of sensitivity to photoperiod. Seedlings do not possess cold tolerance. When seeded in late November, the seedlings are exposed to a short day, which induces the plant to flower in April. Normally, these flower in October and November.

Group III. *Deepwater rice with low photosensitivity.* This group is called Bhadoia and Ashwina.

Plant association of deepwater rice

All the aquatic adaptations are considered primitive according to the evolutionary trend. More accurately, these were not new adaptations; rather, they were the remnants of the evolutionary progenitor of deepwater rice. At least four different types of wild rice are commonly found in the deepwater areas of Bangladesh, particularly in the district of Sylhet, with all the abovementioned aquatic characteristics. In addition, at least three of them are strongly perennial and all of them are highly shattering before full maturity. One, however, locally known as *deo-jhara,* has a long vegetative phase and may be nonphotosensitive. It is mentioned above that a very insignificant group of deepwater rice known as Bhadoia also has a long vegetative phase and is essentially nonphotosensitive.

The systematic position of all these endemic wild rice species is not clear, and these are sometimes referred to as *O. perennis, O. rufipogon, O. spontanea,* or *O. sativa* var. *fatua*. All these wild and cultivated deepwater rice species are mutually cross-compatible. This cross-compatibility might have served as a perennial source of variability in deepwater rice. A thorough study of all these different wild rice species along with the deepwater rice may reveal some facts to establish the origin of rice in a more convincing way. Wild rice is mostly considered as a persistent weed in deepwater rice areas (Ahmad 1974). Other than wild species found in deepwater rice areas, some weedy races, such as *Hygroryza aeristata* (Retz. Nees) and *Leersia hexandra,* commonly occurred in swamps and ditches, habitats with permanent water stands, as small to large populations (Vaughan 1988, Lu and Loresto 1996). Farmers called *L. hexandra* (Swartz) “Arali Ghas,” which means jungle grass.

Table. 1. District-wise (greater) area (ha) of deepwater rice in Bangladesh during the 1970s and 1999.

Greater districts	Area (000 ha)				Percent decrease since 1969-70
	1969-70[a]	Percent of total area	1999[b]	Percent of total area	
Dhaka	212.0	10.2	90.9	13.0	57
Mymensingh	150.4	7.2	6.5	0.9	96
Tangail	100.2	4.8	35.7	5.1	64
Faridpur	314.4	15.1	108.5	26.0	43
Chittagong	22.1	1.0	2.0	0.3	91
Noakhali	83.1	4.0	2.9	0.4	97
Comilla	257.2	12.3	98.0	14.0	62
Sylhet	226.2	10.8	72.6	10.4	68
Rajshahi	154.2	7.4	38.6	5.5	75
Dinajpur	15.6	0.7	0	0	100
Rangpur	26.6	1.3	1.3	0.2	95
Bogra	8.6	0.4	0	0	100
Pabna	183.5	8.8	76.3	11.0	58
Khulna	76.3	3.7	23.9	3.4	67
Barisal & Patuakhali	72.6	3.5	15.3	2.2	79
Jessore	135.7	6.5	16.7	2.4	88
Kushtia	48.3	2.3	35.4	5.2	27
Total	2,087.0	100.0	696.6	100.0	67

Sources: [a]Zaman (1974). [b]Das (2000).

Distribution of deepwater areas

The surface contour of Bangladesh is the decisive factor in the distribution of deepwater areas. The riverine floodplain alluvium of the Ganges, the Brahmaputra, the Tista, the Surma, the Meghna, the Kusiyara, and other rivers occupies about 70% of the country and the remainder is occupied by the northeastern hilly areas, the central Modhupur tract, and the western Barind tract. The floodplain, in spite of its flatness, is often dotted with saucer-shaped *haors* and *beels*, sometimes many kilometers in extension, which are the home of deepwater rice (Ahmad 1974). In many beels, regular deepwater rice cannot be grown because the water is too deep. In those areas, Rayadas might be cultivated (Perez and Nasiruddin 1974).

The total cropping area under broadcast aman or deepwater rice in 1999 was about 700,000 ha, which is 6.8% of the annual coverage of rice in the country (Das 2000). The district-wise distribution pattern of deepwater rice coverage and its percentage in 1969-70 and 1999 are shown in Table 1. In percentage of total rice area in each district, Faridpur was the most predominant for the cultivation of deepwater rice, followed by Comilla, Dhaka, Pabna, and Sylhet, where about 10% or more of the total area was covered by deepwater rice in both 1969-70 and 1999. The districts

Table 2. Locations, water depths, and other names given to Rayadas.

Type	Location	District	Water depth (m)	Other names
12-month Rayada	Kalia	Jessore	4.57–6.10	None
	Molahat	Khulna	4.57–6.10	
	Gopalganj	Faridpur	4.57–6.10	
6- to 8-month Rayada	Fakirhat	Khulna	3.66–4.57	Dacca Rayada, Balam Rayada
	Bagerhat	Khulna	[a]	[a]
	Five unions in Terrokoda	Khulna	3.66–4.57	[a]
	Sripur, Muhammadpur, Salikha, Magura	Jessore	Up to 4.57	Gourkajol (early), Bhoronatha[b] (late), Lal Digha, Lokhi Digha, Bara Digha[b], Sona Digha[b]
	Narail and Lohagara	Jessore	3.05–4.88	[a]

[a]No information available. [b]Has the ability to survive and produce a crop even after uprooting.
Source: Perez and Nasiruddin (1974).

with coverage of 5% to 10% were Tangail and Rajshahi. The rest of the districts had a low coverage. The Chittagong Hill Tract does not grow deepwater rice. In many areas, deepwater rice is grown mixed with the aus crop and therefore the area shown to be covered by deepwater rice is not accurate because 1 ha of such a mixed crop is shown by the BBS as 1 ha of deepwater rice and 1 ha of aus.

The Rayada group encompasses beel tracts on both banks of the Madhumati River in three districts. This area extends from Sripur (Jessore District) in the north to Mollahat (Khulna) in the south, and from Magura, Narail, and Lohagara (Jessore) in the west to Gopalganj (Faridpur) in the east. Farmers also claim that Rayadas can be found in seven *thanas* of Jessore District, four thanas of Khulna District, and at least one thana of Faridpur District (Table 2). Specifically, however, the 12-month Rayada can be found only at Kalia in Jessore, at Mollahat in Khulna, and at Gopalganj in Faridpur. These three areas form a triangle with Kalia in the northeast, Mollahat in the south, and Gopalganj in the east. The Rayada tract covers an estimated 5,180 ha (Perez and Nasiruddin 1974).

Biodiversity

From these notes, we can see that several locations have distinct biotypes:

- Khulna: Rayada and allied varieties/landraces
- Upper Faridpur (Gangetic floodplain): mostly Digha, Bowailla, Sharshoria, etc.
- Dhaka (beel area): Baish bish, Maliabhagar, Lal Aman, Digha

Table 3. Traditional deepwater rice cultivars grown in the 1960s and in 1991 in selected areas of Mirzapur and Deldwer subdivisions of Tangail District, Bangladesh.

Water depth	Cultivar	
	1960s or earlier	1991
Shallow to medium (50150 cm)	Baro Bawalia, Sonna Bawalia Bawalia Digha, Deshi Digha, Horinga Digha, Laxmi Digha Sonna Digha, Depho, Kertikjul Kertik Kaika, Rajpal, Shonmoti	Baro Bawalia, Sonna Bawalia, Bawalia Digha, Deshi Digha, Sonna Digha, Depho
Deep (150250 cm)	Chamara, Dhola Digha, Ejol Digha, Hejol Digha, Haskol Digha, Sonna Digha, Laxmi Kajol, Raja Mondol	Chamara, Dhola Digha, Hejol Digha, Haskol Digha
Very deep (>250 cm)	Hamubhanga, Haskol, Boron, Kaitor, Moni, Shuti Boron, Sheali Boron	None

Source: Islam (1993).

- Meghna east belt: Gabura, Lal Kanai
- Tangail Nagarbari belt: Kaika, Digha
- Jamuna belt (central Pabna): mostly protected by Jamuna embankment
- Sylhet (mostly haor areas): aman group, Laki group

Vanishing genetic resources

From 1969 to 1999, deepwater rice area decreased drastically by about 67% (Table 1). The reduction was not only in area but also in number of varieties. It is obvious that, along with the decrease in area, the number of varieties consequently decreased. The highly localized varieties/landraces/cultivars that were destroyed by severe floods in 1974, 1987, 1995, etc., became extinct. Widely adapted varieties such as Digha, Lal Aman, Vowailla, Sharshoria, etc., are now commonly found. This kind of genetic erosion in rice germplasm, as a whole, may be as high as 40%. Most of the genetic stocks had a very narrow adaptability, which could not withstand biotic and economic stresses, and extinction resulted (Zaman 1997). In a survey in two deepwater thanas of Tangail District, the traditional deepwater cultivars in shallow to medium-deepwater decreased by 30%, in deepwater situations by 50%, and in very deepwater situations by 100% during the last 30 years (Table 3). As irrigation facilities in deepwater rice areas expanded with the installation of low-lift pumps and shallow and deep tubewells during the 1970s and 1980s, farmers could grow modern rice cultivars and high-value crops such as potato and tomato during the boro season (winter). As a result, the area under deepwater rice in 1990 declined to 0.9 million ha, a 56% reduction in the last 20 years (Islam 1993).

This scenario occurred not only in rice. In the last 40 years, all the local wheat varieties of Bangladesh (Mohiuddin, personal communication) and 95% of the once-numerous native varieties of wheat in Greece have been lost forever as victims of recently introduced commercial varieties (Lloyd and Jackson 1986).

Exploration, collection, and conservation

The greater Bengal possessed many indigenous rice varieties (about 15,000) scattered throughout the country. Therefore, the collection program began during the British period in this region. Deepwater rice was collected from 1917 to 1924 and numbered nearly 800 (Haque and Miah 1989). All the collected samples were maintained by growing them in the respective season in each year and the morphological characters were recorded (Alim et al 1962).

The systematic and mission-oriented collection and conservation programs of rice varieties started with the commissioning of a walk-in type of air-cooled gene bank at BRRI in 1974. A nationwide survey was conducted to collect the names, seasons, and locations of the existing cultivated rice varieties through a questionnaire with the help of the Department of Agricultural Extension during 1979-81. This information was documented in the book *Deshi Dhaner Jat (Local Rice Varieties).* This book has been used as a cross reference of existing collections and will help to identify future collections. It contains a total of 12,479 names, including duplicates, collected from 359 out of 464 thanas, in which 3,820 variety names of B. aman (deepwater) rice are listed by thana.

BRRI scientists traveled through most of the low-lying areas of Bangladesh themselves as well as with the help of IRRI germplasm collectors (field advisers). The exploratory collection programs with IRRI were done mostly for B. aman and T. aman rice and *Oryza rufipogon* and its relatives. However, swampy and marshy lands of Dinajpur and valleys of Chittagong Hill Tracts are still unexplored. There is a possibility to obtain *fatua* types of either bold grain, awned/awnless cultivated type or slender/small grain, awned/awnless wild types in those areas.

A total of 659 cultivars of deepwater rice and about 75 samples of wild and wild relatives associated with deepwater rice were collected, catalogued, and placed in short and medium storage in the BRRI gene bank as well as in the IRRI gene bank for safekeeping (Bashar and Sarkar 1997 and personal communication with BRRI gene bank authority).

Evaluation and characterization

Collection and observation of deepwater rice began in 1934 with a few new collections. Since then, studies on pure-line cultivars continue. The number of pure-line cultivars in 1947-48 was 442 and the number has been supplemented annually. All these types are grown and observed annually, with special attention to their purity and yield. All the fixed types, numbering 424, have been classified into 26 popular groups (Table 4). Deepwater rice, like other groups of rice, has various types with

Table 4. Characteristics of deepwater rice on the basis of different groups.

Group types	No. of flowering date	Average	Water level group	Maturity per plant	Tillers grains per panicle	No. of	Color of kernel
Bhadoia	30	22 Aug	Medium	Very early	6.46	117.9	Red
Aswina	19	31 Aug	Medium	Very early	6.46	124.1	Red
Bamoia	10	29 Sept	Medium	Early	7.75	135.8	Red
Bagdar	8	15 Oct	Low	Medium	6.15	138.2	Amber and red
Fulkari	11	15 Oct	Low	Medium	7.90	102.1	Red, amber, and white
Khama	26	17 Oct	High	Medium	7.16	118.3	Red
Laki	83	19 Oct	Low and medium	Medium	7.17	128.7	Red, amber, and white
Bazail	16	19 Oct	Low	Medium	7.69	111.1	Red
Karkoti	13	20 Oct	Low	Medium	7.25	128.9	Red and white
Birain	12	28 Oct	Low	Late	6.51	142.7	Red, amber, and white
Kali Mekri	13	20 Oct	Low	Medium	6.91	143.9	Red
Joal Bhanga	8	21 Oct	Low	Medium	–	–	White and amber
Badal	39	23 Oct	Low and medium	Late	6.55	182.5	Red, amber, and white
Baguaman	9	24 Oct	Low	Late	7.25	145.8	White and amber
Pankiraj	1	24 Oct	Low	Late	–	–	Red and amber
Guai	11	26 Oct	High	Late	5.04	201.6	Red and amber
Dhala Aman	47	27 Oct	High	Late	5.55	208.9	Red and white
Lal Aman	13	28 Oct	High	Late	5.98	166.0	Red and white
Kala Aman	11	28 Oct	High	Late	6.01	191.1	Red
Matia Aman	29	29 Oct	High	Late	5.59	222.8	Red
Pursum	5	28 Oct	Low	Late	7.68	169.0	White and slightly brown
Tilbadam	3	27 Oct	Low	Late	6.26	209.8	Red
Murail	4	29 Oct	Low	Late	6.37	207.5	Dark red
Gutak	1	19 Oct	Low	Medium	7.21	148.2	Red
Lara Aman	1	19 Oct	Low	Medium	5.62	151.2	White
Chaplash	1	19 Oct	Low	Medium	5.77	151.0	White

Source: BRRI (1974).

different names and some similarities in their characters always occur. On the basis of similarities found for different characters such as color of spikelets, size of spikelets, size of rice grains, flowering time, ripening time, and suitability of growing at different water depths, whole groups of deepwater rice have been classified (BRRI 1974). Types with different names may go into one group, for example, Goda Laki Dudh Laki, Katlaki, Shirmain, and Mukut Laki are grouped as Laki. The size and shape of spikelets and rice grains of these types are the same. Sometimes, types with one name may be placed in more than one group. A brief description of all the groups appears in Table 4.

An international standard description list for characterization and evaluation has been developed, in which 62 characteristics are included. On the basis of the descriptor, a preliminary evaluation of about 30% of the deepwater germplasm has

Table 5. List of deepwater rice cultivars showing moderate resistance and resistance to different diseases and insects.

Disease or insect	Cultivar name
Sheath blight	Charock, Sada Pankaich, Kalamanik, Absaya, Kuchi, Kurchi Magi, Dudbazal, Marali
Stem rot	Ghigoj
Bacterial blight	Gabura, Khama, Dali Khama, Bara Bazal, Koia Digha, Asmoita, Hongaza, Ghumsi
Rice tungro virus	Sada Pankais, Hbj A VIII, Laxman Jota
Ufra	Rayada 16-06-1, Sada Pankaioh, Rayada 16-011, Rayada 16-013, Rayada 16-05, Rayada 16-06, Rayada 16-07, Rayada 16-08, Bazail
Green leafhopper	Aswina
Brown planthopper	Gota Bazal, Bara Bazal
Whitebacked planthopper	Khama 4918, Boira Aman
Stem borer	Malia Bhangar, wild floating rice (*fatua*)

Source: Bashar and Sarkar (1997).

been made and 20% has been evaluated under biotic and abiotic stresses (Bashar et al 1995 and personal communication with BRRI gene bank authority). Traditional deepwater rice germplasm with resistance against major diseases and insects is being evaluated regularly with small samples. A total of 36 varieties show moderate resistance to major diseases and insects (Table 5). Traditional deepwater rice also possesses high protein content compared with the aus T. aman and boro groups (Kaul et al 1982). Some of the selected germplasm that possesses above 10% protein content is listed in Table 6.

Use

The exploitation of genetic diversity for varietal improvement is the ultimate objective of genetic resources exploration and conservation. The immediate value of genetic resources depends to a considerable extent on the case with which the breeder can use them. Keeping this idea in mind, geneticists and plant breeders have been working with this vast group of deepwater rice genetic wealth for a long time. However, not much progress has been achieved because of some unavoidable and obvious reasons.

Breeding work on broadcast aman and deepwater rice began at the Dhaka station as early as 1920-21 and about 700 pure lines of deepwater rice were developed. From these, Baisbis, Lalkanai, Dulia, Ghuli, Gabura, Gutak, Notapasha, and Bagrai were selected as the best pure lines and Baisbis and Gabura were released as varieties (Table 7). These two varieties were suitable for a flood depth of 2–3 m with yield potential of about 3 t ha^{-1}. Later on, another pure line with deep purple leaf, Malia Bhangar, was released as a variety for its advantage in eradicating *jhora* rice from the field. On the other hand, Habiganj station was established in 1934 for research on

Table 6. Physico-chemical characteristics of the grains of some selected germplasm of deepwater rice.

Accession no.	Cultivar	Origin	Color	Appearance	Protein %
101	Boro Bhawalia	Dhara	Amber	Medium-medium	10.6
104	ManiK Digha	Dhara	Amber	Medium broad	12.0
106	Bhawal Digha	Dhara	Amber	Medium- medium	11.3
110	Duhd Bhawalia	Dhara	Amber	Medium-medium	10.0
111	Ghoirol	Dhara	Red	Medium-medium	12.2
113	Hashful	Dhara	Amber	Medium-medium	10.8
114	Rajmondol	Dhara	Amber	Medium-medium	10.3
115	Gonok Ray	Dhara	Amber	Long medium	10.4
116	Kalamona	Dhara	Amber	Short broad	10.6
117	Belon dhan	Dhara	Amber	Long medium	10.4
120	Lata	Dhara	Amber	Medium-medium	10.9
121	Lata	Dhara	Amber	Medium-medium	12.1
125	Khoia Motor	Dhara	Amber	Medium-medium	11.0
130	Raj Bhawalia	Dhara	Red	Short-medium	10.5
139	NCP Pasha	Dhara	Red	Medium-medium	10.4
141	Ijol digha	Dhara	Red	Medium-medium	10.0
494	Sungwala	Rajshahi	Red	Medium-medium	10.0
1233	Fulkahon	Rajshahi	Red	Medium-medium	11.6
1235	Chorua motor	Rajshahi	Red	Medium-medium	12.4
1237	Pala Bhir	Rajshahi	Red	Medium-medium	10.0
1238	Luta	Rajshahi	Red	Medium-medium	10.7
1239	Kalamadari	Rajshahi	Red	Medium-medium	10.0
1240	Chingair	Rajshahi	White	Medium-medium	10.6
1271	Gabura	Rajshahi	Red	Medium-medium	10.6
1272	Kaladiga	Rajshahi	Red	Medium-medium	11.2
1273	Bansi Raj	Rajshahi	Red	Long medium	11.2
1275	Joyna	Rajshahi	Red	Medium-medium	10.0
1276	Suna diga	Rajshahi	Red	Medium-medium	10.7
1277	Gour Kojal	Rajshahi	Red	Medium-medium	10.7
1278	Modhu Sail	Rajshahi	Red	Medium-medium	12.8
1279	Raja Morol	Rajshahi	Red	Medium-medium	11.6
1453	Boilam	Dhaka	Red	Medium-medium	13.8
2049	Kar Sail	Khulna	White	Short broad	10.0

Source: Kaul et al (1982).

deepwater and boro rice. At this station, 424 pure lines of deepwater rice were collected and classified into 26 common or local groups—Bagdar, Laki Khama, Fulkari, Bazail, etc. Among these, Khama, Laki, Bazail, and Dhala Aman were widely adapted and each had many subvarieties. By 1946, five deepwater aman varieties—Katiabagdar (Hbj. aman IV), Godalaki (Hbj. aman II), Gowai (Hbj. aman III), Dudhlaki (Hbj. aman IV), and Dhala (Hbj. aman V)—were released from Habiganj (Alim et al 1962). Later, another variety, Lal Aman (Hbj. aman VIII), was also released from Habiganj in 1955 (Table 7). However, out of the total of 6,820 crosses made so far at BRRI headquarters, only 450 lines out of about 70 traditional deepwater rice varieties were

Table 7. List of B. aman (deepwater) varieties developed through pure-line selection.

Name of variety	Station number	Year of release	Life cycle[a] (d)	Yield (t ha^{-1})
Baisbis	DA AI	1941	240	2.8
Gabura	DA AII	1941	225	2.7
Maliabhangar	DA AIII	1943	250	2.6
Katyabagdar	Hbj. AI	1944	210	2.2
Godalaki	Hbj. AII	1946	215	2.9
Gowai	Hbj. AIII	1946	230	2.8
Dudhlaki	Hbj. AIV	1946	225	2.8
Dhala Aman	Hbj. AV	1946	252	2.8
Lal Aman	Hbj. AVIII	1952	250	2.8

[a]Life cycle is based on April sowing.
Source: Miah (1989).

used as parents for the development of high-yielding modern-variety rice (Salam and Das 2000).

Conclusions

Most of the local types became extinct because, once they were destroyed, seeds could not be found in other areas. Examples are Pankhiraj (varieties with extra long glume I and II), Khejur jhupi, or Khejur kandi varieties with clusters of panicles and very bold grains (low market value). Most of the widely adapted varieties are Digha groups, Aman groups, Laki groups, Bajail, Kaika, etc.

However, it is to be noted that farmers do not take care to grow pure varieties. Therefore, a surveyor needs to collect all the varieties/landraces, wild or *fatua* types, and hybrids (between wild and local varieties). Some of these mixtures might be identified by the farmers. Others should be grown and classified. Such an attempt will restore some of the varieties considered to be extinct.

This type of research work needs the immediate attention of BRRI or the newly proposed organization, the National Institute of Plant Genetic Resources; otherwise, these varieties will become lost forever.

Wild rice species also need thorough studies; *fatua* types found in northern areas are not equally adapted for deeply flooded areas. These are the components of biodiversity of deepwater rice, which needs to be conserved and studied well.

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Genetic improvement of flood-prone rice: current status and future prospects

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The increase in productivity of flood-prone rice can be attributed to both germplasm improvement and management technologies. However, the emphasis in this paper will be more on genetic improvement. Traditional rice cultivars grown in flood-prone areas possess tolerance for many different and complex abiotic stresses present in this ecosystem. However, they do not possess high-yielding traits such as dark, broad, and erect leaves and a high number of productive tillers with heavy panicles. The transfer of these traits from high-yielding varieties to traditional cultivars would increase the latter's yielding ability if tolerance for abiotic stresses is retained or improved. Hybridization between the two types is the next step needed to develop the desired plant type. Progress in this kind of germplasm improvement is slow because of the difficulty in selection under field conditions and the presence of other related abiotic stresses. The potential for increasing the yield of elongating rice through conventional genetic improvement methods can be attained only for areas with 100 cm or less water depth because the breeding process is very costly and time-consuming. The exploitation of new technologies will speed up the genetic improvement of flood-prone rice. These technologies provide the tools for accelerating the breeding process, increasing selection efficiency at lower cost, and transferring genes across species and genetic barriers. The combination of conventional breeding and biotechnological tools will ensure success in flood-prone breeding. Participatory plant breeding for flood-prone rice is another promising methodology to understand the selection criteria of farmers and ensure acceptability/adaptability of varieties developed. The challenge is how to capitalize on these novel techniques. This paper will discuss the problems, progress, and prospects in the genetic improvement of flood-prone rice.

To increase the productivity of flood-prone rice, the contribution of both improved germplasm and management is needed. However, this paper emphasizes the genetic improvement aspect. Traditional rice cultivars grown on flood-prone lands possess tolerance for many different and complex abiotic stresses that are present, but they do not possess high-yielding traits such as dark, broad erect leaves and a high number of productive tillers with heavy panicles. Transfer of these traits from high-yielding varieties to traditional cultivars would increase their yielding ability if their tolerance

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for abiotic stresses is retained or improved. Hybridization between the two types is the logical option to develop the desired plant type for flood-prone rice. Progress in this kind of germplasm improvement activities has been slow because of difficulty in selection under field conditions and the presence of other related abiotic stresses. Therefore, other nonconventional genetic improvement options must be explored to fast-track varietal improvement for flood-prone areas. This paper will discuss the problems, progress, and prospects in the genetic improvement of flood-prone rice.

Problems in the genetic improvement of flood-prone rice

From the rainfed lowlands to the very deeply flooded areas of large river basins, uncontrolled floods occur where deepwater or floating rice is grown. Conditions may be temporary submergence of 1–10 days, which affects both rainfed lowland and deepwater rice, long periods of standing water, or daily tidal fluctuations that sometimes cause complete crop submergence. Crops grown in these areas are also affected by adverse soil conditions such as acidity, salinity, minimal toxicities, and low soil fertility.

In deepwater- (80–150-cm depth) and floating-rice (>150-cm depth) areas, soil and water management is difficult. Where the land is fertile, doubling of the yield that farmers obtain is attainable if improved varieties are used. Genetic improvement of floating rice is extremely difficult and therefore may not be a high priority for plant breeding research. In submergence-prone areas where the rice crop remains submerged for 10–12 days but that do not have major soil problems, rice yield can be more than doubled, with the use of improved varieties, as these areas usually have fertile soil and minimal occurrence of pests and diseases.

Current knowledge about interactions between soil- and water-related stresses is limited. Although the physiological mechanisms of submergence tolerance and elongation ability of rice are known, their functions and expressions under different soil conditions are still a mystery. This is a major constraint to the breeding process. Some degree of tolerance for these flooding stresses is available in the germplasm. Appropriate combinations of abiotic stress tolerance that will match the needs of the many different soil conditions of flood-prone areas are required to minimize risks. But limited knowledge of these traits, especially of their physiological mechanisms, biochemical interactions, and inheritance, and the lack of effective screening techniques have slowed breeding progress. Only recently has some information on these traits become available to rice scientists to help them develop effective breeding strategies.

Progress in the genetic improvement of flood-prone rice

Deepwater rice

This type of rice survives excess water by elongating (leaf sheath, leaf blades, and internodes) to keep its foliage above the water level. Deepwater rice accumulates starch before flooding, and this is used for rapid elongation when the plant is submerged. The physiological mechanisms and inheritance of elongation ability in deepwater rice are fairly well understood.

Floating rice of South Asia (such as Jalmagna) differs from its counterparts of Southeast Asia (Baisbish and Rayada 16-3) in terms of elongation ability. South Asian types are faster elongators. Genetic analysis showed overdominance in F_1 of all crosses, indicating a heterotic response of the genes governing elongation. Transgression was always positive with Jalmagna while both positive and negative transgressions were observed in crosses involving Baisbish and Rayada 16-3. This suggests differences in minor genes among the two types. In Jalmagna, the differences led to complementary gene action. Crosses between the two types could produce faster elongation from the better parent. In a separate 7 × 7 diallel analysis, Jalmagna was found to be the best combiner; thus, elongation ability can be combined with derived genotypes (IRRI 1995).

To increase the efficiency of breeding for deepwater rice, research at IRRI has emphasized developing the molecular marker-assisted selection (MAS) technique. In the F_8, recombinant inbred lines (RIL) of the cross IR74/Jalmagna were used to tag the genes governing internode elongation. An amplified fragment length polymorphism (AFLP) marker linkage map was produced and a major gene was mapped on chromosome 1 that explained 85.7% of the elongating ability variation. Other minor genes were located on chromosomes 1, 4, 5, 6, and 10. Identification of the molecular marker closely linked or flanking the important genes will be the next step in developing MAS for elongation ability in rice (IRRI 1997).

Germplasm improvement focuses on prebreeding research on flood tolerance and on providing improved breeding materials to national agricultural research and extension systems (NARES). Varietal improvement work for the Southeast Asian countries was transferred to Thailand at the Prachinburi Rice Research Center (PRC) and Huntra Experiment Station (HTA) in 1994, which became the lead centers for the evaluation and selection of breeding materials.

The Rice Research Institute of Thailand produced two new-plant-type lines, HTA AFR 810442-B-7-1 and HTAFR84038-B-5-0-1, which yield 5.0 t ha^{-1} compared with 3.7 t ha^{-1} for local check variety LPT 123 at 100-cm water depth.

IRRI's research concentrated on improving germplasm for Southeast Asia. Crosses were made between traditional deepwater rice and tropical japonica to produce elongating plant types with sturdy stems and long heavy panicles. By 1995, IRRI's collaborative effort focused on assisting the lead centers in widening the gene pool. IRRI's strategic research in generation advance of bulk populations in the dry season and characterization of advanced lines produced advanced breeding materials that were shared with the lead centers and other interested NARES for evaluation.

Prototypes of the new deepwater rice plant type developed at IRRI were tested in 1995 for yield in the dry and wet seasons. IR11141-6-1-4 (new deepwater rice plant type) was grown in the dry season at 80–90-cm water depth and was compared with IR72 grown in normal irrigated conditions. The experiment was repeated in the next wet season, with four more new deepwater-plant-type lines, two improved deepwater rice lines, and a traditional plant type (FR13A). IR8 and IR74 were added to the irrigated rice variety set. Although deepwater rice is not grown in the dry season, the 1996 dry season experiment showed that the new deepwater rice plant type is capable of yielding as high as modern irrigated rice. The water depth of 80–90 cm seemed to have no effect on yield. Similar results were found in the wet season. The average yield of five new deepwater-plant-type lines was 4.9 t ha^{-1} (flooded) compared with 4.7 t ha^{-1} (normal field) for the irrigated varieties. Yields of the new deepwater plant type were about double those of the traditional plant type and the new deepwater line IR62364-2B-10-2-2 yielded 6 t ha^{-1}. The results demonstrate that new-plant-type yields comparable with those of irrigated rice can be obtained from deepwater areas (80–90 cm) (IRRI 1997).

Very deepwater (>100 cm) elite lines from *Oryza sativa* × *O. rufipogon* crosses were developed. Fifty-two lines were derived from crosses of IR60601 (FR13A/*O. rufipogon*), IR60608 (IR42/*O. rufipogon*), and IR64588 (IR11141-6-1-4/*O. rufipogon*/2*IR11141-6-1-4). They had rapid elongation with increasing water level, high tillering, dense and nonshattering panicles, and erect, broad green leaves.

Submergence-tolerant rice

The physiological mechanism of submergence tolerance is now well understood. Tolerant rice accumulates more starch at a more rapid rate than sensitive rice. This starch is used by alcoholic fermentation to produce energy and so that the plant can stay alive during submergence (Emes et al 1988). Plant survival under submergence depends on two main factors: the supply of O_2 and CO_2 to the plants and irradiance (Setter et al 1995). The gas supply is limited by low diffusion rates in water (10,000-fold less than in air), whereas irradiance is limited by turbidity. When the plant is partially or completely submerged in water, low O_2 supply results in a major shift in the metabolic pathway for energy production, from aerobic respiration to alcoholic fermentation (Setter et al 1997). Alcohol dehydrogenase (ADH) and pyruvate decarboxylase (PDC) are known to be key enzymes in alcohol fermentation, and PDC is a rate-limiting step in this process. Some plants are able to survive the period of submergence but die when subsequently exposed to air, suggesting that oxidative damage may be involved during the recovery phase (Bowler et al 1992). A dramatic increase in superoxide dismutase (SOD) was reported during submergence in a tolerant variety of *Iris pseudacorus*, but not in a susceptible check (Monk et al 1987). This suggests that overproduction of active oxygen species caused by the misdirection of electrons in the photosystem may take place during the recovery phase. The ability to scavenge the active oxygen may play an important role in submergence tolerance.

Submergence tolerance in rice plants can be improved by the incorporation of genes coding for alcohol fermentation and active oxygen-scavenging systems. Such transgenic rice plants are expected to alleviate yield losses caused by submergence. Transgenic rice lines have been produced at IRRI through transformation with ADH and PDC (Quimio et al 2000). These lines showed higher PDC and ADH activities and more ethanol production than an untransformed control. Ethanol production was positively correlated with survival under submergence. These results show the possibility to enhance submergence tolerance by transformation with ADH and PDC. The next step will be to incorporate the genes into varieties that will be accepted by local farmers.

The genetics of submergence tolerance was studied by analyzing the segregation pattern of F_2. Results revealed that FR13A, Kurkaruppan, and Thavalu possess the same genes for submergence tolerance, whereas Goda Heenati has a recessive gene that is nonallelic to the dominant genes of FR13A, Kurkaruppan, or Thavalu (IRRI 1994). Another genetic study showed that a single dominant gene (Mishra et al 1996) governed submergence tolerance.

Marker-assisted selection (MAS) for submergence tolerance is in progress. Gene mapping using F_8 RILs from the cross IR74 × FR13A located the major gene on chromosome 9. Four minor genes were tagged on chromosomes 6, 7, 11, and 12; each of them explained more than 19% of the total phenotypic variation. The gene on chromosome 11 was in the vicinity of the alcohol dehydrogenase genes (*Adh1* and *Adh2*) that were associated with submergence tolerance (IRRI 1997). Previous studies showed that the submergence-tolerance genes of FR13A and Kurkaruppan are different from that of Goda Heenati. With a long-term objective of pyramiding these genes to enhance tolerance, two types of crosses were made in 1992. One cross was to transfer the submergence-tolerance gene from traditional donors to an improved plant-type background. The crosses were IR74/FR13A, IR74/Kurkaruppan, and IR74/Goda Heenati. The other type of cross was made between IR40931-26-3-3-5 and IR31142-14-1-1-3-1-12 (IR66036), both moderately tolerant of submergence. Improved advanced lines developed from these crosses were tested for submergence tolerance. Five highly submergence-tolerant lines with improved plant type were isolated from the cross IR74/Goda Heenati, six from IR74/Kurkaruppan, and 14 from IR74/FR13A. Lines from IR74/Goda Heenati will be crossed with others to pyramid the different genes. Eight lines of accession IR66036 were more tolerant than the parents, indicating the accumulation of genes from different sources. More than 500 elite submergence-tolerant lines with improved plant type and varying tolerance for other biotic and abiotic stresses were identified and categorized. These lines are available for national testing and they constitute a good source of tolerance in national breeding programs.

A replicated yield trial in both submerged (13 days under water) and normal field conditions was conducted in the 2000 dry season. Most of the 10 submergence-tolerant lines with modern plant type had yields comparable with that of IR72 (3.5 t ha^{-1}) grown in a normal irrigated field and much higher than that of the traditional check FR13A (1.2 t ha^{-1}). Under submerged conditions, modern varieties IR72 and IR42 did not survive after 13 days of submergence and thus produced no yield, whereas the submergence-tolerant entries survived and produced yield. One of the new lines yielded 3.4 t ha^{-1}, more than double the yield of FR13A (1.5 t ha^{-1}). The result of this yield trial demonstrates the possibility of increasing the performance of submergence-prone rice by genetic improvement.

Prospects for the genetic improvement of flood-prone rice

The potential for increasing the yield of elongating rice through the conventional genetic improvement method can be attained only for areas that accumulate 100 cm or less water depth. New deepwater-rice-plant prototypes (-100 cm) and improved germplasm with tolerance for submergence are already available, but the breeding process is costly and time-consuming. The exploitation of new technologies that will fast-track the genetic improvement of flood-prone rice is therefore desirable.

Biotechnology in flood-prone rice

Because of recent developments in biotechnology, breeders working on flood-prone rice could now revisit their wish-list traits for a rice plant to produce higher yield under excess water. Biotechnology provides tools for accelerating breeding progress, increasing selection efficiency at lower cost, and transferring genes across species and genetic barriers. The challenge is how to capitalize on these novel techniques.

Most flood-prone rice is photoperiod sensitive; it is cultivated only once a year. Developing a new variety, using conventional breeding techniques, takes about 10 years. This breeding cycle can be reduced to 3–4 years with the use of anther culture. Tissue culture allows somaclonal variation and in vitro selection, thereby shortening the breeding cycle. This type of biotechnology is one of the oldest, but it is widely used and has demonstrated its usefulness in rice breeding.

In conventional breeding techniques, breeders have to depend on the phenotypic expression of genes. Selection efficiency is reduced by this expression when interactions occur. Furthermore, gene pyramiding for multiple traits and enhanced adaptability are impossible to undertake with conventional breeding. With molecular biology techniques, breeders can detect alleles of interest in their materials by using molecular markers in MAS. The MAS technique has unlimited capacity and is nondestructive, rapid, and reliable and it could detect any number of genes of interest at the same time (gene pyramiding). Most of the problems mentioned earlier could be overcome by using the MAS technique primarily because it is not affected by environmental factors. Development of the MAS technique for tolerance of flooding (as mentioned earlier) is in progress at IRRI.

Gene transformation opens new opportunities to solve problems that breeders could previously solve only in their dreams. One good example is the control of stem borer and sheath blight in deepwater rice. There are no known sources of resistance to this insect or disease, and chemical control is costly and unacceptable. Transformation with genes producing insecticidal proteins such as endotoxins of *Bacillus thuringiensis* (*Bt*) and tripsin inhibitors should reduce stem borer damage. Similarly, the chitinase-producing gene can suppress the sheath blight pathogen. Floating-rice cultivars, when transformed with the *Bt* gene, could substantially increase the yield of very deeply flooded rice lands (Dowling et al 1998). A transgenic rice with genes for alcohol fermentation and an active oxygen-scavenging system can improve its submergence tolerance.

With new knowledge on functional genomics, proteomics, and bioinformatics, there is reason to be optimistic in developing the ideal plant type for flood-prone rice.

Farmers' participatory breeding

The combination of conventional breeding and biotechnological tools will ensure success in breeding for flood-prone rice. Participatory plant breeding (PPB) for flood-prone areas is another promising methodology that helps to understand the selection criteria of farmers and ensures acceptability/adaptability of varieties developed. The target traits for flood-prone rice are not only elongation ability or submergence tolerance but also tolerance for other biotic and abiotic stresses. Hence, evaluation and generation advancement will be done in farmers' fields and farmers will do the selection. Under these conditions, selection efficiency could be increased by replication across farmers' fields and seasons. MAS can be done in early generations (F_2 or F_3) and farmers in the target environments will do the selection. This PPB and MAS combination will increase breeding efficiency and ensure the involvement of farmers in target environments and the fast dissemination of varieties developed, which is the ultimate goal of genetic improvement.

After using all these technologies, what is left now is to establish cooperation among breeders, geneticists, stress physiologists, soil scientists, sociologists, economists, plant nutritionists, and biotechnologists. This cooperation and coordination are vital for producing and delivering improved rice cultivars that we need for the future for flood-prone areas.

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Genetic improvement of flood-prone rice: Where are we today and what are the future prospects?

R. Thakur

Flood-prone areas are characterized by a great diversity of growing conditions. More than 20 million ha of rice lands in Southeast Asia are subject to uncontrolled flooding. The problem of excess water occurs in places ranging from the rainfed lowland to very deepwater areas. On these lands, no crops other than rice can be grown. Though yield is poor because of problem soils and unpredictable combinations of flood and drought, the areas support more than 100 million poor farmers and their dependents.

Work on this ecology received global attention when IRRI organized a seminar in Bangladesh in 1974, which provided the stimulus needed and created impetus for research. The problems associated with this ecology have been investigated and remarkable achievements have been made in understanding the various steps involved in the process of breeding flood-prone rice. The inheritance of desirable traits for flood-prone rice such as elongation, photoperiod sensitivity, submergence, etc., has been worked out, suitable screening methods have been developed, and suitable breeding methods have been standardized.

Though great diversity in water depth exists, this ecology is broadly classified in terms of varietal requirements. Since flood-prone rice can be grown once in a year, the breeding cycle is long. Only 12 varieties of flood-prone rice have been released in a period of 20 years. Efforts to breed dwarf varieties with elongation ability have not been as successful as expected, yet they have potential in areas where improved management practices could be used. There is a need to reorient the breeding strategy based on the experience gained over the years. A farmers' participatory approach is required to develop adaptable varieties.

Flood-prone areas are characterized by a great diversity of growing conditions—in amount and duration of rainfall, depth and duration of flooding, frequency and time of flooding, time and duration of drought, soil type, and topography. More than 20 million ha of rice lands in Southeast Asia are subject to uncontrolled flooding in the wet (monsoon) season. Problems of excess water occur in places ranging from the rainfed lowland to the very deepwater areas, where floating rice is grown. Conditions may be temporary submergence of 1 to 10 days, which affects both rainfed lowland and deepwater rice.

In most Asian flood-prone areas, flooding during the wet season occurs from June to November, while maximum water depth occurs from August to October and recession of water starts in September. The main flood-prone rice areas are in eastern India (2.5 million ha), Bangladesh (2.4 million ha), Thailand (0.56 million ha), Vietnam (0.6 million ha), Myanmar (0.55 million ha), Cambodia (0.3 million ha), and Indonesia (1.0 million ha). On these lands, no crops other than rice can be grown successfully in the *kharif* season. Though average yield is poor because of problem soils and the unpredictable combination of drought and flood, the area supports more than 100 million people, mostly poor farmers and their dependents.

Production technology has three key components: variety, management, and protection measures. Among these, the variety is crucial. The development of a variety involves several distinct steps: (1) understanding the target environment, (2) selecting desired/ideal plants in different generations and identifying genotypes with desired traits and determining their inheritance, (3) formulating an appropriate breeding program, and (4) doing effective field testing to isolate cultivars, first at the research station and then in multilocation and adaptive trials for the release of a variety. It is relatively easy to accomplish these tasks in homogeneous environments, but it is difficult in an adverse environment such as flood-prone areas. Yet, in the recent past, remarkable achievements have been made in understanding the various steps involved in the process of breeding flood-prone rice.

Understanding the target environment: India

Flood-prone rice ecology is mostly confined to the eastern Indian states of Assam, West Bengal, Bihar, and Uttar Pradesh (Table 1). Assessment of the area and distribution of deepwater rice, including floating rice, began in 1986 through the ICAR-WB-IRRI Deepwater Rice Project. The new estimate of flood-prone rice area in India is not very accurate but it is the first assessment that has had some field verification (Catling 1992).

Information on flood-prone rice cultivation practices in India is also limited and the available data are mostly scattered in local research papers and unpublished reports. However, based on the information available, areas of four states are summarized below.

Assam enjoys fairly well-distributed rainfall from May to September and receives an average rainfall of about 2,300 mm per year. Flood is a regular phenomenon. Four to six flash floods may occur in a monsoon season.

Assam has five major rice crops and three of them qualify wholly or partially as deepwater rice (Catling 1992):

Bao: Equivalent to broadcast aman, bao is the floating rice that is broadcast in March and April and mostly harvested in November-December. Bao is also sown mixed with jute in low-lying areas.

Sali: Sali is the largest group of rice, covering about 70% of Assam’s total rice area. A large portion of sali cultivars qualify as deepwater rice since these cultivars

Table 1. Extent of deepwater (flood-prone) rice in India.

State	Area (000 h)
Bihar	830
Assam	493
West Bengal	463
Uttar Pradesh	390
Orissa	121
Andhra Pradesh	75
Tamil Nadu	40
Tripura	34
Manipur	20
Mizoram	–
Total	2,466

are tall and are grown to a depth of 70–80 cm for long periods. They overlap with bao rice in many plant characters.

Asra: Asra is broadcast or transplanted mainly in the Barak valley.

Deepwater rice is mostly planted in pure stands but, in a field survey, a quarter of the fields were found mixed with aus rice (Duara 1975).

In *West Bengal*, deepwater rice land is scattered in many districts. Half of the total deepwater rice area is established by broadcasting and the rest is transplanted late at a spacing of 25–30 cm in 50 cm of standing water (De Datta and Banarjee 1978). There is very little mixed cropping of deepwater rice apart from a few aman-aus mixtures grown in some districts. Deepwater rice lands are locally called *bheel*.

For *Bihar*, the major references are Thakur et al (1984), Singh and Saran (1988), Singh et al (1989), and ICAR-WB-IRRI (1989). Bihar has three physiographic divisions: the south Bihar plateau, south Bihar plains, and north Bihar plains. The flood-prone area is concentrated in the north Bihar plains only. Low-lying areas, mostly saucer-shaped or long stripes, which are abandoned river courses, are the real deepwater areas, locally called *chaur* or *man*. They are deeper in the central part and shallow at the periphery. They are scattered all over north Bihar.

Flood-prone rice is usually broadcast-sown mixed with various nonrice crops such as mungbean, sesame, jute, fodder, sorghum, etc. (Thakur et al 1984). Varietal adaptations of different kinds are found. Semideepwater rice is planted on the peripheral parts of chaurs, whereas, in the central parts, floating rice is grown, which possesses the characteristic high rate of elongation in flooded conditions (Thakur et al 1984, Singh and Saran 1988, Singh et al 1989, ICAR-WB-IRRI 1988).

In *Uttar Pradesh*, Watt (1991) reported that floating rice was grown in *jheels* of Gorakhpur District and that it was harvested in November from boats. Knowledge about deepwater rice in Uttar Pradesh comes mostly from unpublished records of ICAR-WB-IRRI (1989), Pathak (1988), and Chauhan et al (1989). Cultural practices and cropping patterns are similar to those in adjoining north Bihar. However, mixed cropping is not very prevalent. Rabi crops are also grown after the harvest of deepwater rice.

Desirable traits and their mechanism of inheritance

Some traits are essential for deepwater rice to survive the rigors of growing conditions. The mechanism of their inheritance is a prerequisite to sound breeding strategies. Tolerance of soil-related problems and major pests and diseases is also required. The essential traits follow.

Elongation

The elongation ability of deepwater rice is considered as an escape mechanism against prolonged submergence. Almost all traditional deepwater and floating rice have various degrees of elongation ability and this is a stable genetic trait. However, it has baffled geneticists in the past and both qualitative and quantitative genes have been reported for controlling elongation ability (Ramaiah and Ramaswami 1941, Kihara et al 1962, Morishima et al 1962, Suppapoj et al 1977, Hamamura and Kupkanchanakul 1979, Nasiruddin et al 1982).

Thakur and Hille Ris Lambers (1987) developed a nondestructive technique to measure elongation ability, which was subsequently used by Dwivedi et al (1992) and Dwivedi and Senadhira (1993) in their genetic studies. Elongation was found to be due to two dominant complementary genes (Thakur and Hille Ris Lambers 1989, Dwivedi and Senadhira 1993) and this has been confirmed physiologically (Suge 1987).

Photoperiod sensitivity

Photoperiod sensitivity refers to plants in which panicle initiation depends on daylength. It is one of the most important traits determining the adaptability of flood-prone rice to different conditions. Most deepwater rice is photosensitive by nature. Flooding pattern varies greatly from place to place and varieties adopted to the flooding pattern of one region may not be suitable for that of another. Photoperiod sensitivity is a controlling factor to make rice fit a specific hydrologic pattern. It allows lengthening of the growing season, so that even an early or late-planted crop will still flower at the right time.

The critical period for rice is the longest photoperiod beyond which the plant cannot flower, and it varies from 12 to 14 hours (Vergara and Chang 1976). The critical photoperiod of Thai and Cambodian deepwater rice varieties varies from 12 to 12.5 hours, while that of Indian and Bangladeshi varieties varies from 13 to 14 hours. If Thai or Cambodian varieties are planted in India and Bangladesh, they flower in late November. On the other hand, because of their critical photoperiod, Indian and Bangladeshi varieties flower in September in Thailand and Cambodia. Neither late November flowering in India and Bangladesh nor September flowering in Thailand and Cambodia is desirable.

The genetics of photoperiod sensitivity has been investigated and one to three dominant genes have been found to be responsible for its control (Chandraratna 1953, Sampath and Seshu 1961, Poonyarit et al 1989).

Submergence tolerance

Prolonged submergence kills some rice varieties more quickly than others. A submergence-tolerant rice variety is one that can survive submergence and resume growth after the water has subsided. Incorporation of submergence tolerance would improve plant adaptation to areas where the duration of submergence does not exceed 2 weeks. Although varietal differences in submergence tolerance have been known for a long time, studies on genetics began only in the late 1970s. This trait is required for areas where flash flood is common and to some extent also in the deepwater ecology.

Tolerance is dominant over susceptibility. A segregation analysis indicated that at least three dominant genes were involved in controlling submergence tolerance: two had duplicate gene action, whereas the third was complementary to either of the first two (Suprihatno and Coffman 1981). Analysis suggested that at least one major gene, or closely allied group of genes, was involved in tolerance (Mohanty et al 1982, Haque et al 1989). According to Ray et al (1990), at least two dominant genes were involved. All investigations found highly significant additive and nonadditive gene effects. Recently, Mishra et al (1996) found submergence tolerance to be due to one major dominant gene.

Some other traits help deepwater rice in its survival, such as kneeing ability, nodal roots, and nodal tillers.

Establishing an appropriate breeding program for developing new cultivars with adaptability and acceptability

Screening

Deepwater rice when broadcast-sown in March-April faces moisture stress during summer. Screening methods were developed by De Datta and O'Toole (1977) for drought tolerance, submergence tolerance, and elongation ability; by Boonwite et al (1977) for submergence tolerance; and by Mazaredo and Vergara (1977) for elongation ability. These methods are widely used, with some modifications. Vergara et al (1977) also developed an easy technique to screen kneeing ability, which is an important trait of flood-prone rice. A nondestructive technique to measure plant and internode elongation was developed by Thakur and Hille Ris Lambers (1986, 1989), which was further perfected by Dwivedi et al (1992).

Researchers in different regions use these screening methods to identify materials/genotypes for use in breeding programs.

Plant type concept

With the success of the dwarf plant type in the irrigated ecosystem, incorporation of the elongating gene in the dwarf plant type became an attractive way to develop modern deepwater rice (Morshima-Okino 1964). Rice variety Leb Mue Nahag (floating) was crossed with IR95 and a semidwarf breeding line of IRRI (IR442) to develop dwarf elongating varieties. Dwarf elongating cultivars were identified after submerging the segregating population at appropriate water depths. One such cultivar, T 442-57, was rated the best at a water depth of around 1 m (Prechart et al 1975).

This existing prototype was distributed widely to various breeding programs and it was believed that its progenies would directly give rise to a series of improved cultivars with conditional elongation for node and flood depth. However, T 442 did not spread and its use was restricted because of two weaknesses: (1) it lacked photoperiod sensitivity and it was not adapted to deepwater areas and (2) it was highly susceptible to rice blast, bacterial blight, and several insects pests. Two IR442 lines were released in Bihar as Panidhan 1 and Panidhan 2, but they did not spread for similar reasons (Catling 1992).

Nevertheless, the concept of the "floating" or "elongating" dwarf was a spur to deepwater rice breeding, which stimulated the making of similar crosses. RD 19 in Thailand was released from a cross between IR162 (dwarf) and Pin Gaew 56 (floating), which is strongly photoperiod sensitive and has many desirable traits. HTA 60 was also released in Thailand; it is semitall with elongation ability.

The deepwater ecology of eastern India, as elsewhere, is highly diverse and unpredictable in water depth and soil factors. Plants have to face many abiotic and biotic stresses. Farmers' management practices are minimum because of risk in cultivation. Therefore, the plant type with short stature, as referred to above, may not be suitable.

It is now believed that tall varieties with desirable traits are required for survival in flooded conditions. However, the desired plant type will have to match various specific environments. Environmental characterization is therefore necessary to develop appropriate varieties that will match field conditions.

Characterizing the flood-prone ecosystem and prioritizing research

Environmental characterization is necessary to classify the ecosystem, but it is laborious and time-consuming. Alternatively, for breeding purposes, a detailed characterization of varieties grown by farmers may be adequate for prioritizing the research agenda. The ecosystem is diverse; therefore, varieties must have genetic elasticity to adjust to its growing conditions. Since time immemorial, farmers have selected cultivars to fit the varying magnitudes of ecological factors. Thakur et al (1984) classified three types of varieties grown in Bihar *chaur* lands. For water depth of around 1 m (semideepwater), nonelongating tall cultivars Darmi, Jagar, Salmot, and Bakol are commonly used, while, for depths around 1.5 m (deepwater), Barogar is a common choice. For deeper areas (floating), a group of varieties called Desaria, which have a high rate of elongation, is popularly grown. In flash-flood areas where submergence occurs for about 1 week once or twice within a season, tall cultivars with submergence tolerance are grown. The crop subsquently does not face deep water. Semideepwater or medium-deepwater areas, where water depth remains around 1 m, constitute a majority of the land. Therefore, this subecosystem should receive high priority for research and development. Keeping in view the overall picture, rice improvement work should be confined to an improved plant type for each subecology that forms the flood-prone ecosystem but requires a different plant type.

Ecological characterization

Semideepwater/medium deepwater

This environment has a water depth around 1 m, which usually remains below 1 m, and stagnant flooding. Some areas overlap with the rainfed lowland environment. Rice is established by broadcast sowing or transplanting.

The desirable plant type is a photosensitive, early maturing type with tall or intermediate height, drought and submergence tolerance, nonlodging habit, long panicles, and kneeing ability.

Deepwater

The water depth is usually more than 1.5 m. The depth is suitable if it is more than 1.1 m, and, up to about 4.0 m, broadcast sowing is common in India.

The desirable plant type is a late-maturing, photosensitive tall cultivar with drought tolerance, elongating ability, kneeing ability, and ability to form nodal tillers. In areas where water depth may be more than 1.5 m, cultivars with high elongation ability where floating rice is cultivated are desirable.

Flash flood

In this environment, floodwater rises quickly and submerges the crop for 1 week once or twice at the vegetative stage. The crop is mostly direct sown and may mature during the rainy period. These areas subsequently may be grouped in the semideepwater category.

Cultivars with intermediate plant height and submergence tolerance and that are photosensitive or insensitive are desirable. Flood-prone rice can be grown only during the wet season. As a result, the breeding cycle is long and therefore more than double the time of the favorable ecosystem to develop a new variety is required (Table 2).

Over the past 20 years, only 12 deepwater rice cultivars were released compared with 95 for irrigated rice. Deepwater rice possesses a large array of plant characters that must be considered and effectively combined (Catling 1992). Methods of reducing the breeding cycle have been suggested. For example, F_1 anther culture is faster but its applicability for indica rice is still doubtful. Shuttle breeding is another approach in which materials are grown at different locations during the dry season, but it is not always applicable to the flood-prone ecosystem because of the photoperiod sensitivity of breeding materials. However, single-seed descent with appropriate daylight treatment is applicable to flood-prone rice. This type of rapid generation advance (RGA) is extremely useful (Ikehashi and Hille Ris Lambers 1979). However, efforts made in the past along this line have not produced the results expected and only a few cultivars have been developed with this method.

Table 2. Time taken to develop and release some improved rice varieties.

Variety	Country where released	Years	Cultural type
IR8	Philippines	4	Irrigated
IR36	Philippines	5	Irrigated
IR42	Philippines	6	Irrigated
SBR 60	Thailand	6	Irrigated
RD 1	Thailand	3	Irrigated
RD 2	Thailand	5	Irrigated
RD 19	Thailand	10	Flood-prone (deepwater)
Alabio	Indonesia	14	Flood-prone (deepwater)
Tapus	Indonesia	11	Flood-prone (deepwater)
Negara	Indonesia	11	Flood-prone (deepwater)
BTA 60	Thailand	15	Flood-prone (deepwater)

Source: Breeding flood-prone rice, edited by D.W. Puckridge and D. Senadhira (1995); Thailand-IRRI Collaborative Program, Prachinburi Rice Research Institute, Thailand.

Breeding methods

Earlier pure-line selection was usually practiced to develop varieties. However, with the advent of high-yielding dwarf varieties and their remarkable success in irrigated systems, focus was placed on this plant type even for the deepwater ecology, but no tangible success has been achieved. A hybridization program was vigorously pursued and dwarf high-yielding varieties were kept as one of the parents to contribute to high yield. The segregating populations were exposed to the desired environment in well-managed deepwater tanks/fields. A few varieties were released for water depth around 1 m: Manindra (IR34/KLG 6978 143-2P//IR2070-2-5-6/Hbj DW 8) and Jogen (IR26/SML 40-10-4) in West Bengal, Jalpriya (IET 4060/Jalmagna) and Barh Avarodhi (Madhukar/Sona) in Uttar Pradesh, and LPR 95-2 (Pankaj/Jagnath//Negheribao), LPR 96-10-1 (Pankaj/Jagnath//Negheribao), and LPR 96-12 (Pankaj/Jagnath//Negheribao) in Assam. However, there are no reports about their adoption pattern in the specific ecologies for which they have been recommended.

A high-yielding deepwater rice variety, RD 19, derived from crosses between IR262-43-8-11 (semidwarf) and Pin Gaew (traditional floating rice) was recommended in Thailand in 1979. It did fairly well in water depth of about 1 m but it did not spread because of its grain chalkiness. HTA 60, which was released recently, however, has had some success.

Although pure-line selection did not receive emphasis, it did result in the development of some popular varieties. Sabita in West Bengal (Mallik et al 1988), Vaidehi in Bihar (Thakur et al 1994), and Jalnidhi in Uttar Pradesh are examples. This method is thus considered to be still valuable for the deepwater rice ecology (Thakur 1995).

Breeding efforts for deepwater environments have so far not been very rewarding and traditional cultivars are still predominantly grown. This warrants a reorientation in strategy. The breeding program has to be realistic. One fact is clear: this ecology is diverse and one may not always aim to develop high-yielding varieties; rather, emphasis needs to be placed on developing varieties with wider adaptability and stable yields. A quantum jump in yield, as found in favorable irrigated systems, is not feasible now in deepwater environments.

Since there is a strong regional specificity for varietal adaptation, local cultivars must be the base parent in the hybridization program. One has to be extra careful in choosing the donor. It need not always be dwarf. We believe that dwarf varieties are high yielders. Moreover, crosses between tall and dwarf varieties invariably take a long time to provide uniform progenies. Based on our experience, crosses between parallel varieties are perhaps ideal and are suggested. Because the parental varieties may differ in few traits, fixation may not take many years.

The farmer participatory breeding approach (Sperling et al 1993, Joshi and Witcombe 1995) may be useful in selecting and testing deepwater cultivars. In general, segregating populations are grown at the research station and selection is done over several years, till a cultivar is uniform. These cultivars are again tested before being released. Varieties released through this process do not neccessarily match the field conditons. However, there is a need to modify the program as in Thailand, where segregating populations are grown in farmers' fields and selection is based on their performance. This approach has been successful (Thakur 1995). Even testing uniform or semiuniform cultivars differing in height, quality, and duration over several years in farmers' fields may lead to the identification of suitable cultivars for release.

A trial consisting of 10–15 entries was conducted and managed by farmers. It faced drought at the early stage and flood later on. The environment was heterogeneous. In this trial, TCA 48 was found to be highly drought tolerant and was recommended for release as Vaidehi (Thakur et al 1994). Growing segregating populations in the typical deepwater land, selecting plants based on the survival of the fittest principle and that possess desirable traits, and repeating of the selection cycle is perhaps the best method for identifying appropriate cultivars.

Future prospects

Considering the vast areas of several countries under the flood-prone rice ecosystem and the support it provides to about 100 million people who are mostly resource-poor farmers and their dependents, several concerns will continue to remain important in these countries. Concerted efforts to develop suitable varieties started nearly two decades back. In the research institution involved, financial allocations for flood-prone rice are usually meager even though this ecosystem is more complex than other rice environments. However, with the experience gained in various aspects of breeding, a reorientation in the breeding approach so as to develop adaptable varieties is needed. Priority should be given to the growing conditions that vary from place to place; consequently, many varieties are needed to suit specific local conditions. Cultivars meant for specific locations are preferred by local farmers as these cultivars perform better under adverse conditions, though their yield is usually not high. Pure-line selection should continue as a tool to developing new varieties. This process has helped to develop some very good varieties that are cultivated on a large scale. In any hybridization program, local varieties must be kept as one of the parents and the donor parent should differ, preferably in few traits, so that fixation takes place in a few generations. The segregating population should be exposed to real growing conditions so that selected progenies will possess tolerance of adverse conditions. In areas where water depth is below 1 m, intermediate plant height is desirable. International cooperation in this endeavor is also desirable for the exchange of germplasm.

The flood-prone ecosystem is complex yet amenable to various management practices such as mixed cropping with nonrice crops and integration with dry-season boro rice. We hope that the unique wide genetic diversity of flood-prone rice will be well exploited to develop improved germplasm to meet the needs of poor farmers and consumers.

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Strategies for increasing the productivity of rice in medium-flooded areas of Bangladesh

M.A. Salam, P.S. Biswas, and M. Akhlasur Rahman

Flash-flood submergence, medium-deep stagnant, and shallow-flooded deepwater rice (within 100 cm flood depths) subecosystems are discussed in this paper. Major constraints to, varietal needs in, and strategies for varietal development in these subecosystems are discussed. BR11, BRRIdhan 32, and BRRIdhan 38 showed moderate tolerance for flash-flood submergence. Chechua and Arman Sardar had submergence tolerance similar to that of FR13A. Several advanced lines were developed with tall seedlings and tall plant height and were expected to be adaptable to the medium-deep stagnant subecosystem. Several deepwater rice (DWR) lines were identified that could tolerate submergence by slow stem elongation and maintain plant height to coincide with flood depths. These lines showed significantly higher yields than local DWR checks in farmers' fields.

Seasonal flooding is common in Bangladesh. Annual flooding at depths of 50 cm to 2.5 m constitutes the flood-prone rice-growing environment. Areas flooded at 60–90 cm are considered to be shallow-flooded and are discussed in this paper. Flooding at these depths is a major constraint to rice production because of submergence and waterlogging. Short-duration submergence (7–10 d), called flash flood, often occurs as a result of localized excess rainfall in areas where drainage is slow (Fig. 1). On the other hand, prolonged stagnation flooding >50 cm for 2–3 months because of ponding of water without drainage is called medium stagnant water (Fig. 1). Again, submergence lasting beyond 10 d usually kills rice plants unless they emerge from the water through leaf and stem elongation (Mukharji and Roy 1979). The flooding pattern of this category is described as deepwater rice-growing conditions by several authors (Duara 1975, Maurya 1976, Saran 1977). Traditional varieties have grown in these rice production systems with low yield. This paper describes the progress made and future needs for varietal development in the shallow flood-prone environments.

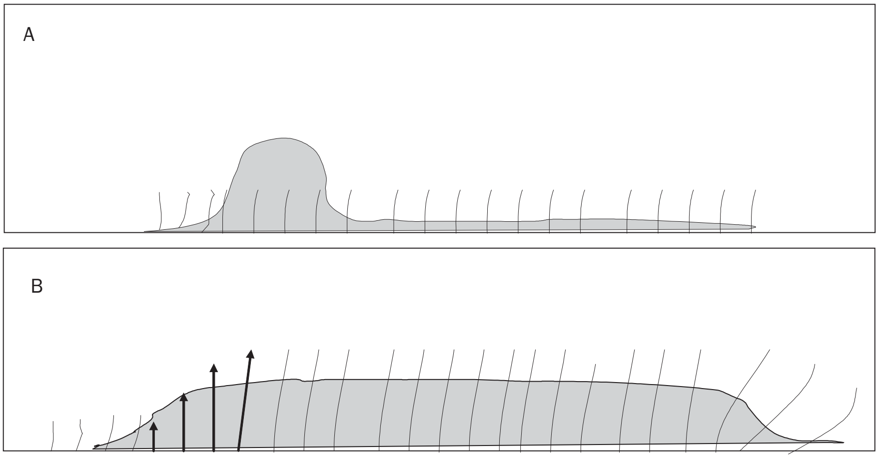

Fig. 1. Schematic hydrographs of flash flood (A) and medium stagnant water (B) rice field (Hille Ris Lambers and Seshu 1982).

Progress made on varietal development for the flash-flood subecosystem

The characteristics of this environment are the sudden submergence of the rice crop for 10–15 d any time between transplanting and the maximum tillering stage because of heavy rainfall or the onrush of early monsoon floodwater (Miah 2000). However, the early tillering stage of the rice plant is the period most vulnerable to submergence. Recovery of growth after submergence is considered to be the most important adaptation mechanism (Miah 2000). FR13A is used as a submergence-tolerant check. It can tolerate complete submergence of 10 days (Hille Ris Lambers and Gomosta 1986). The evaluation of modern varieties showed that BR11, BRRI dhan32, and BRRI dhan38 had a moderate degree of tolerance at 10 d of complete submergence. Very few progenies have been made by using FR13A in breeding programs. It is important to note that advanced breeding materials were screened for submergence tolerance, but ignoring early generation progenies. As a result, tolerant materials are not properly identified. Recently, screening of local varieties showed that Chechua and Arman Sardar had submergence tolerance similar to that of FR13A (BRRI 2000).

Constraints of the flash-flood subecosystem

- Submergence may be more than 10 d
- Poor crop establishment because of submergence at the tillering stage

Varietal needs for the flash-flood-prone subecosystem

- Submergence tolerance of 10–15 d
- Fast recovery after submergence

Table 1. List of photoperiod-sensitive advanced breeding lines with tall seedlings and plant height, T. aman, 1998.

Designation	Seedling height (cm)	Plant height (cm)	Purba, Keoa, Sreepur[a] Days to maturity	Purba, Keoa, Sreepur[a] Yield (t ha^{-1})
BR4766-3B-1	61	130	158	3.4
BR4974-27-4-1-1	44	145	158	3.6
BR4974-2-1-1-6-3-2	53	140	155	3.4
BR4974-23-1-6-1	59	137	148	3.8
BR4974-45-9-2	58	137	158	3.0
BR5323-16-4-1	56	142	158	3.3
BR(BE)6155-47-3-6	62	130	153	3.8
BR22 (standard check)	40	116	152	2.6

[a] Water depth during transplanting was 30 cm and increased to 60 cm at maximum tillering stage.

Breeding strategies for the flash-flood subecosystem

- Combining ability of local varieties should be determined and efficient use made of the general combiners in breeding programs, unlike FR13A, a poor combiner.
- Early generation screening should be done under proper environmental conditions and attention should be given to recovery ability of the selected progenies.

Progress made in the medium-deep stagnant (MDS) subecosystem

Water depth during crop growth ranges from 50 to 80 cm and water is stagnant for 2–3 months in the MDS subecosystem. Traditional varieties have been grown in this environment with low yield. Several advanced lines were developed possessing sufficiently tall seedlings and tall stature that were moderately resistant to lodging and had potentially higher yields than the standard variety (Table 1). The photoperiod sensitivity of the lines would lead to flowering coinciding with the reduced water depth in the field at the end of October to early November. Therefore, evaluation of these materials in farmers' fields in different MDS areas is in progress.

Constraints of the medium-deep stagnant subecosystem are (1) poor crop establishment because of submergence at transplanting, (2) reduced tillering because of a prolonged period of waterlogging, and (3) proneness to submergence at any time of the vegetative growth phase.

Varietal needs for the medium-deep stagnant subecosystem are (1) tallness of seedlings from 50 to 60 cm within 40–50 d after seeding, (2) photoperiod sensitivity for use of aged seedlings with required tallness, (3) tall stature (130–150 cm) with sturdy stem, and (4) good tillering habit in a waterlogging situation.

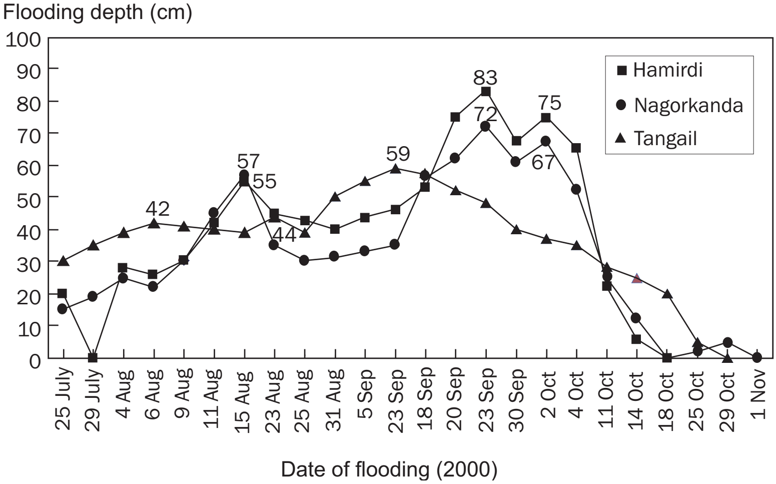

Fig. 2. Flooding patterns at IFAD sites, Maligram (Bhanga) and Tuparia (Gopalganj), deepwater rice, 1999.

Breeding strategies for the medium-deep stagnant subecosystem are the collection of locally adapted varieties from different MDS areas that have been cultivated regionally by farmers, a combining ability test for identification of donors and for use of general combiners in breeding, and early generation screening of progenies in a waterlogging situation.

Progress made in the shallow-flooded DWR subecosystem

The construction of civic structures such as embankments, sluice gates, polders, crossroads, etc., controls and stabilizes flood depths within 1.0 m in many DWR areas of different floodplains (Figs. 2 and 3). The Digha group of early varieties has been grown at Bhanga, but varieties Joyna, Goirkajol, Khoiamotor, etc., with medium growth duration, are popularly grown at Gopalganj. These DWR varieties possess the fast elongation habit of leaf and stem with low grain yield potential. The low yield of DWR varieties is considered to result from their large stature, irrespective of flood depths (Fig. 4), such that most of the energy is used for developing vegetative growth.

Breeding lines developed at IRRI showed a positive response to flood depths such that their leaf and stem elongation coincided with the flood depths to limit submergence and maintain the required plant height (Fig. 4). This physiological adjustment in plant height of the genotypes is important to conserve the energy necessary for grain yield. These advanced lines had shorter stature and significantly higher yields than the local varieties (Table 2). It is important to note that these advanced lines had yield potentials of >4.0 t ha^{-1} in rainfed lowland rice conditions. Further-

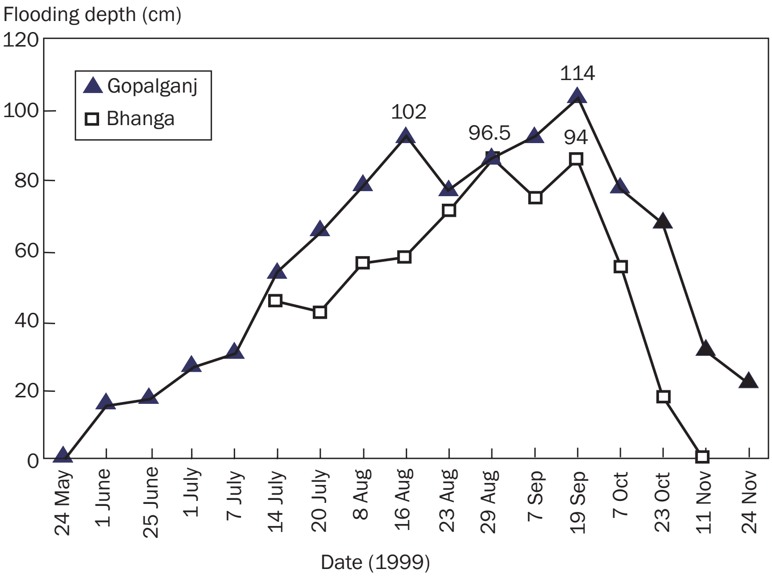

Fig. 3. Flooding patterns at three trial sites, IFAD, deepwater rice, 2000.

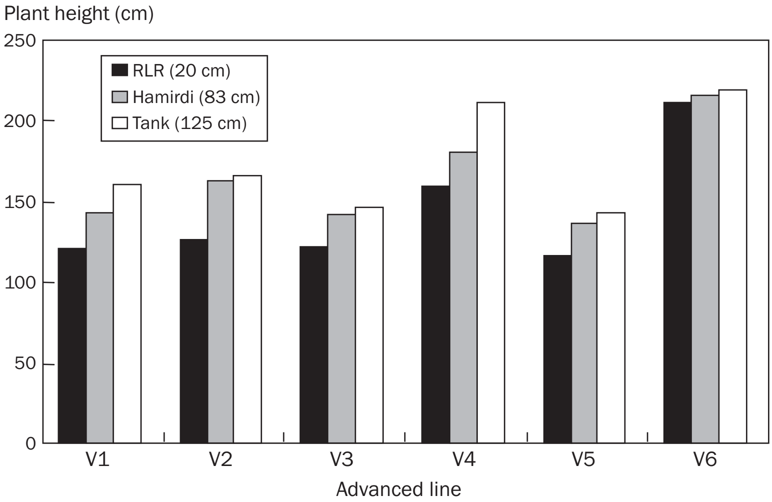

Fig. 4. Response of plant height of the selected deepwater rice (DWR) advanced lines at different flood depths, IFAD, DWR, 2000. V1 = IR64588-47-2-2B-12-1-2-3, V2 = IR64588-47-3-2-2B-9-2-3-3, V3 = IR60436-B-65-2, V4 = PCR89114-B-R2-2-2-1, V5 = IR62653-8-3-3, and V6 = Hijoldigha (local check).

Table 2. Yield and growth duration of advanced lines tested in rainfed lowland (RLR) and deepwater rice (DWR) areas, IFAD sites, 2000.

Designation	Days to maturity[a]	Yield (t ha^{-1})				
		RLR	DWR, IFAD sites[b]			
			Hamirdi	Nagorkanda	Tangail	Mean
IR64588-47-3-2-2B-12-1-2-3	196	4.3	2.4	1.5	1.6	1.8*
IR64588-47-3-2-2B-9-2-3-3	194	4.2	2.1	2.0	2.1	2.1**
IR60436-B-65-2	186	4.7	2.2	1.3	1.6	2.0**
PCR89114-B-R-2-2-2-1	182	2.9	2.8	1.5	2.0	2.1**
IR62653-8-3-3	189	4.0	2.3	1.6	1.7	1.9*
Hijoldigha/Chamara (local checks)	186	1.6	1.6	0.8	1.1	1.2
LSD (5%)						0.51
LSD (1%)						0.72

[a]Average of three locations. [b]Flooding patterns of the DWR, IFAD sites are shown in Figure 3.

more, these lines showed a maturity duration more or less similar to that of the local checks Digha and Chamara.

Constraints of shallow-flooded DWR are extravagant vegetative growth and poor response to nitrogen application.

Varietal needs for shallow-flooded DWR are slow elongating type, growth duration similar to that of local varieties, adjustment of plant height to coincide with flood depth, and responsiveness to nitrogen management.

Breeding strategies for shallow-flooded DWR are a combining ability test for slow elongating genotypes and the use of general combiners in breeding programs, early generation progeny selection of slow elongating types at 100-cm flood depths, and the evaluation of slow elongating genotypes in shallow-flooded DWR areas of the Padma, Jamuna, Meghna, and Ganges floodplains.

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Adopting modern rice technologies in flood-prone areas: status, constraints, and opportunities

N.M. Miah, A.U. Ahmed, and B.A.A. Mustafi

Rice is the most important crop in Bangladesh and it is grown in four seasons. About 80% of the arable land is under rice cultivation. The adoption of modern rice varieties is about 62%. Among the rice crops, deepwater rice is affected by flood to a variable extent and there is no modern technology adoption in this area. Two basic development strategies can be followed to increase agricultural production in flood-prone areas: providing flood protection and improving crop production without flood protection. Certain biophysical and socioeconomic problems identified need to be solved.

Bangladesh has a land area of 14.85 million hectares, of which 10.65 million ha are cultivable. The rice-growing area has a very diverse environment, starting from a drought-prone upland to a deep-flooded situation of more than 3 m water depth. Rice, the staple food crop, covers about 80% of the arable land and accounts for 94% of food grain production (Nasiruddin 1997). On average, Bangladeshis derive 76% of their daily calories and 66% of their protein intake from rice.

Rice is grown year-round in four growing seasons in Bangladesh: aus (March to July), transplanted aman (July to December), broadcast aman or deepwater rice (February to November), and boro (November to April). Internationally, rice-growing environments have been classified into five major categories (Khush 1984) as follows: (1) irrigated, (2) rainfed lowland, (3) deepwater, (4) upland, and (5) tidal wetlands.

In Bangladesh, rice is grown in all of these environments. The rice seasons generally fit into the major environmental categories, with boro representing irrigated, T. aman representing rainfed lowland, aus representing upland, and B. aman representing deepwater conditions. However, with the increasing adoption of modern rice technology, these associations are fading. For example, the introduction of modern varieties in the aus season with the help of initial irrigation to establish the crop is expanding the scope of transplanted aus (T. aus) rice. Likewise, with partial irrigation to overcome late-season drought, modern varieties are being used in many

Table 1. Flood depth and extent of flooding in Bangladesh (million ha).

Flood depth (cm)	Year of		
	Low flood	Average flood	High flood
0–6	–	–	–
61–120	1.40	1.87	1.76
121–180	1.75	1.01	1.06
Above 180	1.92	5.87	6.88
Total	5.07	5.87	6.88
% Total	40.91	47.33	55.41

Source: Zaman (1986).

rainfed lowland areas. In general, deepwater, upland, and tidal wetlands are considered as unfavorable rice environments. Tidal wetlands occupy a large area of the southern coastal region of Bangladesh, which poses unique environmental problems as well as opportunities.

Flood-prone areas of Bangladesh

It is rather difficult to ascertain the areas normally flooded, the depth of flooding, and the time and duration of flooding. Floodwater comes from the major rivers of the country: the Brahmaputra, the Ganges, and the Meghna. In general, water stage in the major rivers, local rainfall occurrence with cyclonic weather in the Bay of Bengal, etc., determine flooding potential. Each year, about one-third to half of the country is under the grip of flood during the monsoon months (Zaman 1986).

Zaman (1986) estimated that the total flood-prone area, depending on the severity of flood, varies from 5.07 to 6.88 million ha (Table 1). This flood-prone area can be subdivided into flood-prone but not drought-prone, and flood- and drought-prone areas, which cover about 2.20 and 1.0 million ha, respectively. The lowlands, in which both drought and flood can affect rice crops, are found in the greater districts of Bogra, Pabna, Rajshahi, Kushtia, Jessore, Khulna, and Faridpur (Fig. 1).

The landscape of Bangladesh is characterized by 20 physiographic units, which can be broadly grouped into three land forms. Hill areas account for 12%, terrace areas cover 8%, and floodplain areas cover 80% of the country (MPO 1986). Six million hectares are subject to annual inundation, with flooding depth ranging from 30 to 200 cm. The time of arrival, depth, and duration of flooding, and the rate of water rise, largely determine the timing and choice of crop production practices. The land resources of Bangladesh have been classified into five land types on the basis of flooding depth (Table 2). For the purpose of planning, the country has been divided into five regions: northeast, northwest, southeast, south-central, and southwest. Information on the regional land use for major crops has been developed. Land use in each region for different types of rice is shown in Table 3.

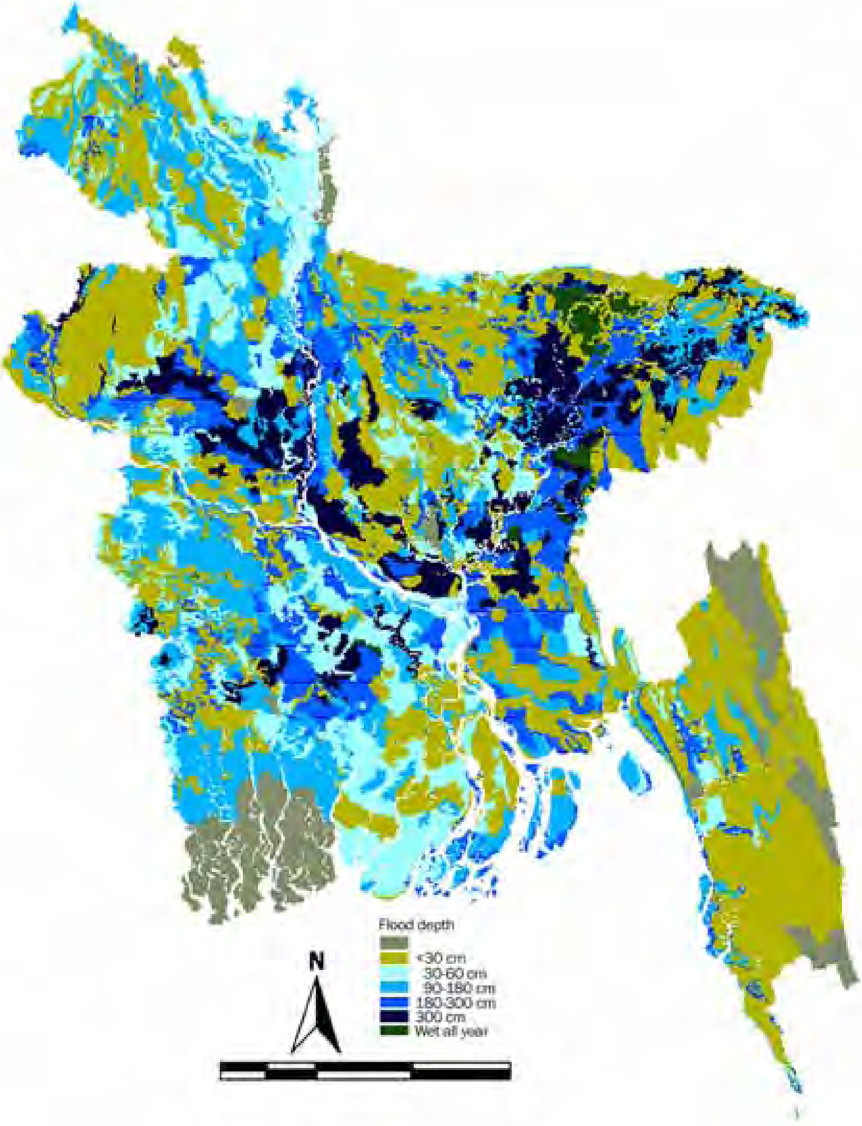

Fig. 1. Flood-prone areas in Bangladesh. This map was generated by IRRI's geographic information systems laboratory in the Social Sciences Division. The source map came from the Local Government Engineering Department of Bangladesh and the source data from the Bangladesh Agricultural Research Council's Land Resources Inventory Database.

Table 2. Land types defined on the basis of flooding depth, Bangladesh.

Land type	Description	Flood depth (cm)	Nature of flooding	Remarks
F_0	Highland	0–30	Intermittent	Land suited to HYV[a] rice in wet season
F_1	Medium highland	31–90	Seasonal	Land suited to local varieties of aus and T. aman
F_2	Medium lowland	91–180	Seasonal	Land suited to B. aman in wet season
F_3	Lowland	>180	Seasonal	Land in which B. aman can be grown in wet season
F_4	Lowland to very lowland	>180	Seasonal/ perennial	Land on which the depth or rate or timing of flooding do not permit growing of B. aman

[a]HYV = high-yielding variety.
Source: MPO (1986).

Table 3. Regional land use (area in million ha) by different rice crops, Bangladesh (1984-85).

Rice crop[a]	Region					
	Northwest	Northeast	Southeast	South-central	Southwest	Total
B. aus	0.621	0.617	0.231	0.314	0.386	2.169
HYV aus	0.120	0.173	0.159	0.095	0.038	0.585
B. aman	0.221	0.437	0.201	0.203	0.303	1.368
L.T. aman	1.224	0.755	0.277	0.547	0.432	3.235
HYV aman	0.215	0.322	0.315	0.108	0.078	1.038
L. boro	0.017	0.297	0.016	0.016	0.016	0.362
HYV boro	0.249	0.454	0.180	0.051	0.076	1.010

[a]HYV = high-yielding variety, L = late, and L.T. = late transplanted.
Source: MPO (1986).

Rice crops affected by flood

Among the rice crops, deepwater rice (DWR), T. aman shallow, and medium-deep stagnant water situations and to some extent irrigated boro rice are affected by flood to a variable extent. DWR at the early growth stage suffers from drought and with the onset of monsoon it suffers from variable degrees of flooding that may last up to the reproductive stage. The approximate areas of DWR in South and Southeast Asian countries are shown in Table 4. Bangladesh has the second-largest DWR area, with India having the largest. Typical flooding patterns during the DWR growing season at two locations in Bangladesh and one location in Thailand are shown in Figure 2.

Table 4. Approximate area of deepwater rice in South and Southeast Asia by country.

Country	Area (000 ha)		
	Water depth of 50–100 cm	Water depth >100 cm	Total
India	2,030	1,400	3,430
Bangladesh	1,050	1,400	2,550
Vietnam	440	420	860
Thailand	450	400	850
Myanmar	520	180	700
Cambodia	80	440	520
Indonesia[a]	300	100	400
Nepal	100	50	150
Others[b]	200	0	200
Total	5,170	4,390	9,660

[a]Potential area for deepwater rice exceeds 1 million ha. [b]Sri Lanka, Bhutan, Lao PDR, Philippines. Source: Catling et al (1988).

Catling et al (1988) defined DWR as rice that is usually grown in land that is flooded to more than 50-cm depth for 1 month or more during the growing season. This definition is based on Khush (1984), with the added stipulation that flooding must be sustained for at least 1 month to distinguish it from tidal wetlands (where water may rise more than 50 cm by tidal action but only for a short period each day) and from shallow flash-flood areas (where rice may be submerged 50 cm or deeper for up to 10 days). In Bangladesh, 47% of DWR area is shallow-flooded (30–90 cm), 21% is medium-flooded (91–183 cm), and 10% is deep-flooded with a water depth of more than 183 cm (Nasiruddin et al 1988). In some countries, rice grown in water depth of more than 300 cm is called floating rice. The growth stages of typical DWR variety Chota Bawalia of Bangladesh are shown in Figure 3.

The onset of flooding in Bangladesh may vary from year to year, but usually it begins in June, attains maximum depth in August, and starts receding from mid- to late October. The flooding pattern of four locations in Bangladesh is shown in Table 5.

The next rice crop that is affected by flood is T. aman, which is affected by flash flooding from the sudden onrush of water because of intense rainfall locally or because in upper areas the crop has been transplanted. The crop may suffer from submergence for 3–7 days or sometimes even for 10 days depending on the location. About 22% of the T. aman crop is grown in flood-prone areas (Zaman 1986).

The high-yielding boro rice may also be affected by flash flooding at the reproductive stage, especially if longer maturity varieties such as BRRIdhan 29 are growing in low-lying areas because of the quick accumulation of early monsoon rainfall.

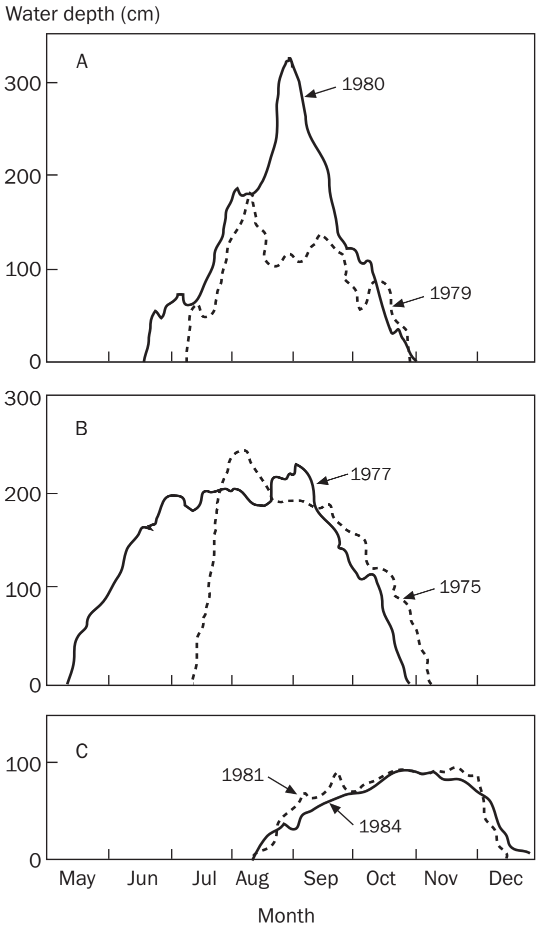

Fig. 2. Flooding patterns in deepwater rice fields in (A) Agrakhola, Dhaka, Bangladesh, 1979 and 1980; (B) Habiganj, Sylhet, Bangladesh, 1975 and 1977; and (C) Huntra, Ayutthaya, Thailand, 1981 and 1984.

Most of the late-planted and late-maturing boro crops suffer from this situation in the Brahmaputra-Meghna floodplain.

Available modern rice technologies in Bangladesh

The Bangladesh Rice Research Institute (BRRI) has so far released 40 modern rice varieties for different ecosystems except the deepwater ecosystem. Among these varieties, 3 are recommended for upland aus conditions, 13 for both T. aus and boro seasons, 7 for only the boro season, and 17 for the T. aman season. For the DWR ecosystem, seven traditional varieties suitable for variable water depths were recommended many years ago and these continue till now (Das 2000). It may not be out of

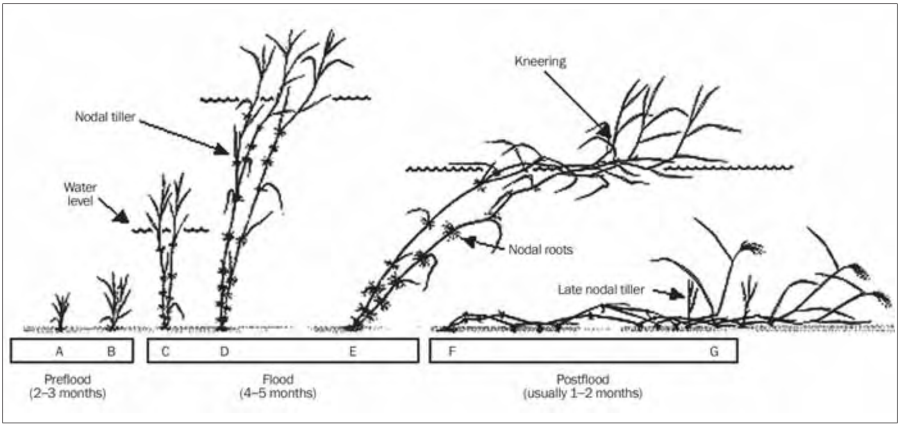

Fig. 3. Growth stages of Chota Bawalia, a traditional floating rice of Bangladesh (adapted from Catling 1992): (A) seedling; (B) basal tillering; (C) early elongation; (D) elongation, with nodal tillering; (E) full elongation: (F) prepanicle initiation, with kneeing and part of stem floating; (G) milk stage, with stems prostrate except for terminal section.

place to mention here that farmers still grow many traditional varieties in areas where modern varieties, which are mostly dwarf or semidwarf in height, have not been found suitable for the prevailing water regions. Tables 6, 7, and 8 show the modern varieties recommended for the T. aman, boro, and deepwater ecosystems.

Several improved DWR breeding lines have been developed for a water depth of up to 2 m but, because of their low and fluctuating yields from year to year, none of these could be released as a variety. Table 9 has a list of improved DWR lines.

Besides BRRI-developed modern varieties, several high-yielding varieties (HYV) were introduced in the country in the late 1960s for aus, boro, and T. aman seasons: IR8 for T. aus and boro (from IRRI), IR5 and IR20 for T. aman (from IRRI), Purbachi for T. aus (from China), and Pajam for T. aman (from Malaysia). Among these, Purbachi is still being grown in the boro season because of its early maturity. In addition, rice varieties IRATOM 24, Binasail, BINA Dhan 4, BINA Dhan5, and BINA Dhan6 were released by the Bangladesh Institute of Nuclear Agriculture (BINA) for the T. aman and boro seasons. The Bangladesh Agricultural University (BAU) has released two varieties, BAU 63 for the boro season and BAU Dhan2 for the T. aman season. All the above varieties of BINA and BAU are recommended only for favorable environments.

Besides modern varieties, BRRI has also developed some improved rice-based cropping patterns and management practices for the flood-prone rice ecosystem.

Present status of the adoption of modern technologies in flood-prone areas

In general, the adoption of modern technologies (varieties) increased from 23% in 1980-81 to 62% in 1999-2000 (BRRI 2000). Current adoption of modern varieties is

Table 5. Flooding characteristics in some deepwater rice fields in Bangladesh, based on daily depth readings (after BRRI and unpublished data, Catling et al 1988).

Item	Northeast Bangladesh		Central Bangladesh		
	Habigang		Agrakhola	Manikganj	Sonargaon
	1975-88	1977-80	1977-80	1986-88	1986-88
Date of inundation	7 June	29 May	23 June	14 July	14 June
Rate of water rise (cm d^1)					
20–50	10.4 ± 4.7	8.3	12.5	13.4	8.1
50–100	5.9 ± 4.1	5.4	4.3	8.4	5.4
100–150	6.1 ± 4.9	3.4	4.6	14.2	3.6
150–200	4.2 ± 2.9	2.5	1.9	13.4	7.4
200–250	8.7 ± 6.5	–	6.9	8.6	–
250–300	–	–	8.8	–	–
Duration of flooding (d)					
above 50 cm	133 ± 20	141	113	91	130
100	109 ± 19	114	75	64	103
150	72 ± 34	71	34	50	61
200	41 ± 20	29	22	45	70
250	29 ± 10	–	–	25	29
300	–	–	–	14	–
Total	144 ± 21	155	123	118	150
Maximum depth (cm)	238 ± 42	211	227	300	265
Date of maximum depth	16 Aug.	16 Aug.	22 Aug.	7 Sept.	24 Aug.
Date of recession	28 Oct.	30 Oct.	22 Oct.	9 Nov.	10 Nov.
Rate of recession:					
from 150 to 10 cm (cm d^{-1})	38 ± 15	44	49	41	53

Source: Catling (1992).

32% in aus, 48% in T. aman, and 40% in the boro season. Together, this depicts the rate of modern variety adoption in favorable environments.

The DWR environment covers the most flood-prone areas in Bangladesh and, as there is no modern rice variety developed and introduced yet for these areas, there is no modern technology adoption in these areas.

Consequently, regions that have more flood-prone rice lands have adopted fewer modern varieties. For example, traditional (local) varieties are grown in flood-affected T. aman areas and the adoption of local varieties in the T. aman season in Region 9 (Dhaka and Tangail districts) is the highest (41%), followed by 24.3% in Region 5 (Jamalpur, Mymensingh, and Kishorganj). Another survey indicates that flood-prone lowland T. aman areas have only 10% adoption of modern varieties (BRRI 2000).

Table 6. List of modern rice varieties recommended for T. aman season, Bangladesh.

Variety	Plant height	Maturity duration (cm)	Yield (t ha^{-1}) (d)	Year of release
BR4	125	145	6.5	1975
BR5[a]	145	150	3.5	1976
BR10	125	150	6.5	1980
BR11	125	145	6.5	1980
BR22[b]	125	150	5.0	1988
BR23[b]	125	150	5.5	1988
BR25	135	135	4.5	1992
BRRIdhan30	120	145	4.5	1994
BRRIdhan31	115	140	5.0	1994
BRRIdhan32[c]	120	130	6.0	1994
BRRIdhan33[c]	105	120	4.5	1997
BRRIdhan34[a]	120	140	2.7	1997
BRRIdhan37	125	140	3.7	1998
BRRIdhan38[a]	130	140	3.8	1998
BRRIdhan39	103	125	4.0	1999
BRRIdhan40[d]	110	145	4.0	2000
BRRIdhan41[d]	115	145	4.0	2000

[a] Fine grain, aromatic. [b] Photoperiod-sensitive and suitable for late planting up to mid-September. [c] Early maturity, suitable for rice-wheat areas. [d] Tolerant of salinity.
Source: Das (2000).

Table 7. List of modern rice varieties recommended for boro season only, Bangladesh.

Variety	Plant height (cm)	Maturity duration (d)	Yield (t ha^{-1})	Year of release
BR17[a]	125	155	6.0	1985
BR18	115	170	6.0	1985
BR19	110	170	6.0	1985
BRRIdhan28	90	140	5.0	1994
BRRIdhan29	95	160	5.0	1994
BRRIdhan35[b]	106	150	5.3	1998
BRRIdhan36	85	140	5.7	1998

[a] Suitable for low-lying haor areas. [b] Tolerant of brown planthopper.
Source: Das (2000).

Table 8. List of traditional varieties recommended for deepwater rice season, Bangladesh.

Variety	Suitable for water depth (m)	Flowering time	Yield (t ha^{-1})	Year of release
Gabura	2.5	End of September	1.5	1941
Maliabhangar[a]	2.5	End of September	1.5	1943
Habiganj AmanI	1.5	End of September	2.0	1944
Habiganj AmanII	2.0	Mid-September	2.0	1946
Habiganj AmanIV	2.5	Mid-September	2.5	1946
Habiganj AmanV	3.0	Early November	2.0	1946
Habiganj AmanVII	3.0	Early November	2.0	1955

[a] Has purple stem and often used to eradicate volunteer rice.
Source: Das (2000).

Table 9. List of improved deepwater rice breeding lines developed from BRRI, Bangladesh.

Pedigree/variety	Suitable for water depth (m)	Flowering date	Yield time (t ha^{-1})
BR224-2B-2-5	2.0	20 Oct.	3.3–5.3
BR308-B-2-4	2.0	22 Oct.	3.3–5.3
BR5915-B-7	2.0	23 Oct.	1.5–2.0
BR5915-B-34	2.0	24 Oct.	1.5–2.0
BR5915-B-43	2.0	23 Oct.	1.5–2.0
IR33727-BR15-5-1-1	2.0	23 Oct.	2.0–2.5
Lakshmidigha (traditional)	2.0	1 Oct.	2.5–3.0
Habiganj AmanIV (check)	2.0	20 Oct.	2.0–2.5
Habiganj AmanVIII (check)	3.0	5 Nov.	1.5–2.0

[a] Tolerant of ufra disease.
Source: Miah (2000).

Constraints to the adoption of modern technologies in flood-prone areas

In a way, the environment itself is the main constraint to the adoption of any new technologies in flood-prone areas. Agricultural production loss from flood occurs almost every year and serious destruction of crops is also common (Tables 10 and 11). The recent devastating flood of 1998 caused the highest loss of paddy, which amounted to about 3.0 million t (Mustafi et al 1999). The two most important factors that determine crop production in a flood-prone area are flood depth during the monsoon and the occurrence of flash flood or storm surge (MPO 1986). Constraints to rice production in flood-prone areas can be grouped into physical, biological, and socioeconomic factors.

Table 10. Major crop loss caused by floods in different years, Bangladesh.

Years	Rice (000 t)	Jute (000 t)	Sugarcane (000 t)
1964	321	318	na[a]
1970	1,298	606	na[a]
1974	1,500	354	172
1980	283	37	172
1988	2,110	26	375

[a] na = not available.
Source: Mustafi et al (1999).

Table 11. Yearly rice crop losses caused by flood and drought, Bangladesh.

Years	Rice production (million t)[a]	Flood/drought loss (million t)	Losses as a % of total potential production
1972-73	9.9	0.25	2.5
1974-75	11.1	0.75	6.1
1978-79	12.7	0.10	0.8
1980-81	13.7	0.44	3.1
1983-84	14.3	0.59	4.0
1987-88	15.4	2.11	13.7
1997-98	18.9	2.00	10.6

[a]Clean rice.
Source: Mustafi et al (1999).

Physical factors

Submergence of the rainfed lowland rice crop (T. aman) during both early and late growth phases and of the irrigated rice crop (boro) during the maturity stage is very common. Drought at the early crop growth stage of DWR is also frequent in Bangladesh; both drought and flood may occur in the same area, but at two different times of the crop season.

Declining soil fertility is another important physical production constraint. Organic matter content, the main indicator of soil fertility, has declined in many places to as low as less than 1%, whereas a good soil should have an organic matter content of 3.5%. More than 60% of the net cultivated area of Bangladesh has organic matter content of less than 1.7%. In addition, zinc and sulfur deficiencies have appeared on 4 and 2 million ha, respectively (Das 2000).

Farmers do not practice balanced fertilizer application. For modern rice, farmers normally apply 75% of the recommended nitrogen fertilizer, 12% of the recommended phosphate, and 6% of the recommended potash.

Biological factors

- Nonavailability of suitable high-yielding varieties:

For T. aman, varieties with submergence tolerance for at least 7 days are needed for submergence-prone areas and medium-deep stagnant water conditions. Varieties that have tall seedlings, intermediate to tall plant height, sturdy culm with no elongation, moderate tillering capacity (8–10 fertile tillers), and photoperiod sensitivity are required for stable high yields.

For DWR, drought tolerance at the seedling stage, internode elongation ability, kneeing ability, photoperiod sensitivity, high panicle density, and high panicle weight are desired for good yields but not available now. Other constraints include

- Nonavailability of good-quality seed of traditional DWR varieties
- Lack of tolerance for existing major diseases and insects
- Poor seed quality arising from farmers' lack of knowledge and/or lack of practice of improved methods of seed selection and storing
- Poor maintenance of seed purity

Socioeconomic factors

- Nonavailability of improved cultivation technology
- Nonavailability of timely fertilizer and other inputs
- Nonavailability of credit to needy farmers
- Most cultivators are tenants and as such do not have an interest in long-term land quality improvement
- Small landholding/farm size
- Lack of adequate extension of technical knowledge to farmers
- Frequent natural hazards and crop failure create barrier to investing more in agriculture

Opportunities to increase production in flood-prone areas

Essentially, two basic development strategies can be adopted to increase agricultural production in flood-prone areas: (1) provide flood protection and (2) improve crop production without flood protection (Brammer 1988). In general, improvement of crop production without flood protection is simpler and less costly than flood protection. Options to increase rice production only are discussed here. Modern technologies that are available are not generally suitable for flood-prone areas except in the boro season. Therefore, it is not surprising that, whereas the adoption of modern varieties in the boro season is the highest in the country (94%), no modern technology is adopted in producing DWR, which covers about 15% of the net cultivable area.

Options for increasing the production of flood-prone rice areas are discussed below by season.

Table 12. List of advanced breeding lines suitable for rainfed lowland medium-deep stagnant conditions, Bangladesh.

Pedigree	Seedling height (cm)	Plant height (cm)	Maturity (d)	Yield (t ha^{-1})
BR 4972-91-13-2	34	132	159	3.9
BR 4973-41-2-6-4	34	125	155	3.6
BR 4974-23-1-6-1	59	137	148	4.3
BR 4974-27-4-1-1	44	145	158	3.6
BR 4974-2-1-1-6-3-2	33	140	155	3.4
BR 4766-33-1	61	130	158	3.4
BR 4766-33-44	42	136	145	3.0
BR 4994-13-2-1	30	124	143	4.8
BR 5323-16-4-1	56	142	158	3.3
BR 5226-13-1	33	128	145	4.6
BR 5226-15-2	33	123	145	4.6

Source: Miah (2000).

T. aman season

Modern variety coverage in T. aman areas is now about 48%, which is accounted for by the use of modern varieties in favorable areas only. The modern dwarf varieties are too short for the unfavorable T. aman areas such as medium-deep stagnant water situations. Recently, BRRI's varietal development program has isolated some advanced breeding lines with the desirable plant type. Out of these, BR 4994-13-2-1, BR 5226-15-2, and BR 5226-13-1 were found to be promising (Table 12). Immediate steps should be taken to release these as varieties and a seed production program should be taken up for their dissemination to farmers.

Boro season

As the adoption of modern varieties in the boro season is already very high (94%), efforts should be directed to stabilizing boro yields. The following measures could be undertaken:

- Distribution of high-quality seeds of modern varieties to farmers. An effective farmer-to-farmer seed exchange program could be used for the purpose.
- Development of more early maturing varieties, which would avoid flash-flood damage at the maturity stage.
- Adoption of integrated pest management (IPM) and integrated nutrient management (INM) packages by farmers for zero or low chemical use for crop protection and for ensuring balanced nutrition to the crop.
- Wide dissemination of information on modern rice production technology among farmers.
- Direct wet seeding of boro rice may be promoted for increased yield, earlier maturity, and reduced water use.

Table 13. Suggested approximate cut-off dates for transplanting modern-variety boro and the following deepwater rice crop in different floodplains of Bangladesh.

Boro variety	Cut-off date for boro transplanting	Approximate date of boro harvest	Cut-off date[a] for DWR transplanting
Meghna floodplain			
BR1, BRRIdhan28, BRRIdhan36	12 Jan	27 Apr	11 May
BR14, BRRIdhan35	7 Jan	27 Apr	11 May
BR3, BRRIdhan29	28 Dec	27 Apr	11 May
Jamuna floodplain			
BR1, BRRIdhan28, BRRIdhan36	22 Jan	7 May	21 May
BR14, BRRIdhan35	17 Jan	7 May	21 May
BR3, BRRIdhan29	7 Jan	7 May	21 May
Ganges floodplain			
BR1, BRRIdhan28, BRRIdhan36	31 Jan	16 May	30 May
BR14, BRRIdhan35	26 Jan	16 May	30 May
BR3, BRRIdhan29	16 Jan	16 May	30 May

[a] Seedling age— 45 days for BR1, BRRIdhan28, and BRRIdhan36 and 50 days for BR3, BR14, BRRIdhan29, and BRRIdhan 35.
Source: Miah et al (1994).

Deepwater rice

Varietal improvement research for the past three decades did not produce any fruitful result in the form of a variety. Improvement of plant type is rather difficult because of the harsh environment through which DWR completes its life cycle. Other options to improve the productivity of the DWR system should be explored.

- For boro varieties grown in DWR areas, irrigation and other management practices such as IPM and INM should be extensively used.
- Programs for seed purification and the production of high-quality seeds of the existing popular DWR varieties should be taken up throughout the country.
- In many of the DWR areas with 2 m or higher water depths, where farmers are growing boro rice only, transplanting of DWR after harvesting the boro crop is possible, which will give an additional yield advantage of 2.0 t ha^{-1}. One such scheme for three floodplain areas is shown in Table 13. This system should be explained.
- DWR can be transplanted along with boro rice such that DWR will be ratooned at the time of the boro harvest, providing an additional yield of 1.0–1.5 t ha^{-1} in areas where water depth is 1 to 2 m. The combination of boro and DWR varieties needs to be selected.

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Crop management

Challenges and strategies in rice crop establishment for higher productivity in flood-prone environments

V.P. Singh, N.V. Hong, A.R. Sharma, and M.P. Dhanapala

This paper reviews research results and farmers' practices for improving the productivity of rice grown through appropriate methods of crop establishment (in flood-prone environments). The two major methods of crop establishment used in these environments are direct seeding and transplanting. Several variants within each method have evolved through years of empirical research and farmers' experiences. These practices are highly dependent on the rainfall pattern, the internal and surface drainage characteristics of the land, and, to some degree, the socioeconomic conditions of farmers. Direct seeding is of two types: dry or wet seeding, the former being adopted extensively by farmers. For transplanting, the use of conventional seedbed-propagated seedlings is most common. The clonal tillers, or dapog-raised seedlings, are used in specific situations. Among the factors affecting crop establishment, timely seeding and transplanting are crucial. Adjusting the seed rate and dibbling seeds in direct seeding, the use of healthy seedlings produced through lower seeding densities in the nursery, nursery fertilization with N, hardening and conditioning of seedlings, and their proper handling before transplanting contribute to successful crop establishment and eventually to improved productivity.

For more than 30 years, growth in rice production was achieved through increased yield, most of which was obtained in irrigated areas. Trends in past years, however, reveal that rice productivity was leveling off in the irrigated ecosystem (IRRI 1993). The area planted to rice is also on the decline as rapid industrialization and urbanization are claiming large areas of prime rice lands. Furthermore, the water availability for rice cultivation in irrigated areas is declining because of the deterioration of irrigation facilities and the increased municipal and industrial demands for freshwater.

The rice supply must come from rainfed areas, including flood-prone lands, and these areas will continue to play an important role in meeting total rice demand. Since such areas occupy a substantial portion of total rice lands, even a small increase in their productivity will increase the global rice supply. Crop establishment status determines the productivity of rice to a great extent. This paper deals with various aspects of crop establishment in different flood-prone environments in which rice is grown.

Flood-prone rice environments

Flood-prone rice environments are characterized by very diverse agroclimatic and socioeconomic conditions. Flood-prone rice lands include rainfed shallow submergence-prone and medium-deep waterlogged lowlands, deepwater areas, and tidal wetlands (IRRI 1984). The flooding and flood-water-recession patterns in these lands are largely determined by rainfall and the drainage characteristics of the land. Catling (1992) provides a detailed description of flood-prone environments.

Rainfed shallow submergence-prone rice lands experience frequent short-term flooding that may damage or destroy the crop when varieties and management practices other than those specifically adapted to this environment are used. Otherwise, the water regime is generally favorable in these areas.

Rainfed medium-deep rice lands accumulate water at depths of 25–50 cm for a substantial period of the growing season. Short-term crop submergence may also occur. One of the major problems associated with these conditions is the growth depression or toxicity caused by stagnant water remaining in the field for months during the crop season.

In South and Southeast Asia, 21% of the rainfed lowland area was classified as shallow submergence-prone and medium-deep waterlogged (Garrity et al 1986).

About 13 million hectares of deepwater and tidal wetland rice are harvested annually, mostly in South Asia. An estimated additional 18 million ha are not being used in South and Southeast Asia. Deepwater rice areas are those where rice grows on rainfed dryland or under shallow flooding for the first 1–3 months or for a little longer and is then flooded to depths that exceed 50 cm for 1 month or longer. These areas are found in the river basins of the Ganges and Brahmaputra in India and Bangladesh, the Irrawaddy in Myanmar, the Mekong of Vietnam and Cambodia, and the Chao Phraya in Thailand.

Tidal wetlands, on the other hand, occur on the coastal belts where water depth in the fields fluctuates according to the tidal movement.

Rainfall, being mostly uncertain and irregularly distributed, usually determines the difference between a high or low crop yield, or a total crop failure because of submergence, drought, or both. However, in flood-prone rice environments, crop damage usually results from prolonged submergence.

Submergence in itself is more harmful at crop establishment and in the tillering stage than later. When the submergence depth is below 50 cm, it can do very little harm to a rice crop that grows to the normal height. If this submergence occurs on fallow land and water depth is receding, farmers can cope with it by delaying the crop establishment time. When the submergence is up to 1 m depth, as long as its timing is past tillering, farmers can choose a late-maturing cultivar to solve the problem. Because farmers did not recognize these possible options, submerged areas were, as a class, excluded from the popularization of modern varieties. A refined analysis of submergence-prone areas in India (Singh and Singh 1996, 2000) showed that the shallow-flooded ecosystem is larger in area than was hitherto estimated. Medium-duration high-yielding varieties (HYVs) can be promoted in these areas. In the

Table 1. Methods of crop establishment commonly used in rainfed rice ecosystems.

Ecosystem/ subecosystem	Method[a]		
	Direct seeding		Transplanting
	Dry seeding	Wet seeding	
Upland	*		
Rainfed lowland			
Shallow, favorable	*	*	*
Shallow, drought-prone	*		*
Shallow, submergence-prone	*		*
Shallow, drought- and submergence-prone	*		*
Medium deepwater	*		*
Deepwater	*		*
Very deepwater and tidal wetlands	*		*

[a] * indicates common practice, blank space indicates no practice.

semideep lowlands (50–100 cm deep), later maturing semidwarf varieties can be propagated. There was a misconception among researchers that cultivars with intermediate plant height were needed for submerged areas. At the development-worker level, there was a misconception that HYVs were unsuitable for all rainfed areas.

Crop establishment in flood-prone environments

Successful crop establishment is the most important factor affecting productivity in flood-prone environments. Much research has been conducted for developing methods of crop establishment that are appropriate to different flood-prone environments. In addition, innovative farmers have also developed crop establishment practices using their years of experience and observations.

Successful crop establishment in these environments is highly dependent on the rainfall pattern and the internal and surface drainage characteristics of the area. Farmers practice two major crop establishment methods, with many variants within each: direct seeding and transplanting. Table 1 outlines the different methods of crop establishment that evolved through years of formal research and farmers' experiences.

Direct seeding

Timely sowing is a nonmonetary input and is of great importance and relevance in rainfed rice. Sowing time is the most critical factor affecting initial crop stand and its subsequent establishment in the field. However, sowing time is determined by the onset of monsoon, land type, and availability of farm resources such as seed, fertilizer, power, and labor.

Farmers in Asia practice two types of direct seeding: dry or wet seeding. Dry seeding of rainfed rice is common in all rice-growing states of India and in Sri Lanka, Bangladesh, Myanmar, Thailand, Indonesia, and the Philippines. Dry seeding may be done by either broadcasting on dry or wet soil or by drilling or dibbling. Large areas of India's rainfed rice lands use dry broadcasting before the onset of monsoon to establish the crop. Direct seeding is advantageous in areas with a very short growing season, since time is gained in establishing the crop early. It is also appropriate in areas where deep water is expected early in the season. Early establishment improves the chances of the crop to withstand flooding successfully.

In rainfed lowlands, the time available for sowing the crop is very limited as a few heavy monsoon showers early in the season may result in the accumulation of water in low-lying fields, rendering direct seeding unfeasible. Sowing should be done soon after the receipt of premonsoon showers. Light showers received in early May should be used for land preparation, thus allowing sowing in relatively dry soil. In coastal Orissa, India, the probability of weekly rains after mid-May is observed to be more than 70% and monsoons become active from mid-June onward (Reddy et al 1989). Rice in these areas should therefore be sown in mid-May to ensure stable yields. Delayed sowing in June was found to be risky, resulting in variable crop performance. By this analysis, in most of the rainfed lowland areas of eastern India, the crop must be sown no later than the first week of June for it to better withstand water stress later in the season.

Direct seeding in dry soil before the onset of the monsoon also has its disadvantages. Adverse weather conditions after sowing, such as early alternate wet and dry spells, may result in poor crop stand because of the drying of germinated seeds or the emerging seedlings. However, in rainfed intermediate lowlands at Cuttack, Orissa, as well as in uplands at Hazaribagh, Bihar, despite poor germination, the early sown crops performed better than the late-sown crops (Sharma 1994a, IRRI 1993) as the late-sown crops, which had relatively better germination, suffered from excess water immediately or a few days after germination. The loss in yield with delayed sowing was not compensated for even with the use of 50% more seeds and N fertilizer.

Another disadvantage of early broadcasting in dry soil is the loss of seeds because of birds, rodents, and ants because many seeds are left on the soil surface. This method also results in uneven crop stand because of differences in the time of germination. Seeds on the soil surface, or at shallow depths, germinate ahead of those in deeper depths. To remedy this situation, drilling of seeds to a depth of 6 cm was found to give good crop yields (Sharma and Reddy 1992, IRRI 1993) and a light planking after sowing protected the seeds from birds, etc.

In some soil types, light showers (<10 mm) after sowing followed by a prolonged dry spell may result in surface crust formation hampering the emergence of germinating rice seedlings. Under such conditions, drilling/dibbling of seeds in clusters (hills) resulted in better emergence than sowing in continuous lines (Jha and Gangadharan 1989, Sharma and Reddy 1992). Drilling/dibbling resulted in better crop establishment and likewise facilitated mechanical weed control and fertilizer application. Drilling/dibbling of rice at an interrow spacing of 20 cm and 15 cm

Table 2. Effect of three sowing dates and N rates (kg ha^{-1}) on the performance of rice under intermediate deepwater conditions (15–50 cm) in India.

Sowing date	Panicles m^{-2}		Panicle weight (g)		Grain yield (t ha^{-1})		Straw yield (t ha^{-1})	
	1988	1989	1988	1989	1988	1989	1988	1989
20 May (20 kg N)	91	155	2.07	1.86	1.48	2.66	4.50	4.79
30 May (40 kg N)	87	126	1.95	2.01	1.38	2.41	3.88	4.02
10 June (60 kg N)	22	90	2.53	1.72	0.22	1.22	0.30	2.39
S.E.	3.4	3.1	0.054	0.054	0.036	0.057	0.109	0.111

Source: Sharma and Reddy (1992).

between hills was found to be appropriate for areas with erratic premonsoon rains (IRRI 1993).

The optimum seed rate to obtain an adequate initial plant population is an important consideration in rainfed conditions where drought is experienced at sowing and excess water after germination. These events lower germination and result in the suppression of tiller formation, death of tillers, and eventual reduction in yield. It is believed that the use of more seeds to increase the initial plant population mitigates the effects of these adverse conditions. Results of several experiments have indicated an optimum seeding density of 400–600 seeds m^{-2} for excess water situations at Cuttack, Orissa, India, and 500 seeds m^{-2} for drought conditions at Hazaribagh and Faizabad for optimum productivity (Ghosh et al 1988, Sharma 1992a, IRRI 1993).

In many situations, it is not possible to complete sowing in time because of delayed rains or heavy rains early in the season and nonavailability of seeds, labor, power, and other resources. Under these situations, suitable adjustments could be made up to an extent by which the productivity of late-sown crops could be maintained. Seed and fertilizer rates could be increased, besides the selection of an appropriate variety for the late-sown conditions. In rainfed lowlands subject to excess water stress, the yield of relatively late-sown (30 May) crops with 40 kg N ha^{-1} was the same as with the crop sown on 20 May with 20 kg N ha^{-1} (Sharma and Reddy 1992). This suggests that an increased fertilizer dose can compensate for the loss in yield caused by delayed sowing (Table 2). However, very late sowing, for example, in June, resulted in such a drastic reduction in crop stand that neither the use of 50% more N fertilizer nor the increased amount of seeds had any beneficial effect. These results point to early sowing as the key management practice for higher productivity in rainfed lowland rice.

Another rainfed rice cultivation system that is common throughout eastern India is "beushening." It is practiced in areas with highly variable climates and where farmers have a poor resource base. It involves mainly dry broadcast seeding of traditional tall cultivars using higher seed rates, wet plowing, and laddering of the same piece of land that has 25–35-day-old seedlings and about 15–20 cm of water on it, and seedling redistribution. Beushening is reported to enhance rice yields under low levels of inputs and uncertain climatic conditions through effective weed control, stimulated root growth, and optimum plant stand (Maurya 1989). Beushening, however, is unsuitable for semidwarf short-duration cultivars as their grain yield decreased significantly because of plant breakage during wet plowing and laddering (Singh et al 1994). Further, beushening is only practiced on lands where at least 15–20 cm of water accumulation takes place and traditional tall rice cultivars of more than 120 days' duration are used.

Wet seeding of pregerminated seeds on well-leveled puddled land is practiced in limited areas in India. It is not so popular because its success is highly dependent on the specific characteristics of the dry and wet transition periods at the onset of the monsoon and adequate surface drainage.

Transplanting

Although direct seeding has been found to be superior to transplanting in rainfed lowland areas prone to excessive waterlogging (Reddy and Panda 1988), there are still large areas where the crop is established through transplanting. This is because of the shorter time period available for sowing, flooding of low-lying fields because of heavy rains early in the season, and the accumulation of water to greater depths during the initial seedling and tillering stages. However, transplanting is risky where water accumulation immediately after planting can put excessive water stress on the young seedlings, resulting in greater plant mortality and reduced tillering. Risk can be reduced by transplanting taller, relatively older seedlings.

In different parts of eastern India, floods occurring at planting time may keep fields inundated for almost 1 month or more, making timely transplanting of rice difficult during this period. Likewise, the late onset of monsoon also delays transplanting. Under such conditions, farmers often resort to bunch planting of overaged seedlings of long-duration rice cultivars to mitigate the harmful effects of excess water. Although these varieties escape complete submergence through quick elongation, their recovery is often poor during the postflood period because of lodging.

Semidwarf varieties developed for excess-water conditions are resistant to lodging and possess an adequate degree of tolerance for submergence and recovery after the recession of floodwater. However, their seedlings raised conventionally in nursery seedbeds do not establish properly when transplanted in water that is too deep. This problem may be overcome by manipulating the seeding density in the nursery, by applying adequate N fertilizer to nursery seedlings, and by using rightly aged seedlings at the time of transplanting (Tables 3 to 5). Seedlings from the fertilized nursery have a well-developed root system, heavier dry weights, and greater N concentration in the plant tissue at the time of transplanting and thus were better able to withstand the ill effects of flooding. This resulted in 2–5 times higher grain yield compared with the unfertilized seedlings (Panda et al 1991, Sharma 1992b, Sharma and Reddy 1993). However, higher tissue nitrogen content in the seedlings at the time of submergence has been noted to cause greater mortality from submergence

Table 3. Survival percentage[a] (%) of rice plants as influenced by seeding density in the seedbed, seedling age at transplanting, and duration of submergence after transplanting, Philippines.

Seeding density[b]	Duration under submergence (d)			
	7	11	15	19
40-day-old seedlings				
SD1	100	100	59 b	8 b
SD2	100	100	85 a	33 a
SD3	100	100	92 a	46 a
SD4	100	100	100 a	40 a
Mean	100	100	84	32
20-day-old seedlings				
SD1	100	44 b	22 a	6 a
SD2	100	89 a	33 a	0 a
SD3	100	89 a	44 a	2 a
SD4	100	67 ab	30 a	6 a
Mean	100	72	32	3

[a] Within each seedling age, means in a column followed by a common letter are not significantly different at the 5% level by Duncan's multiple range test. [b] SD1 = 50 kg seed 250 m^{-2}, SD2 = 50 kg seed 500 m^{-2}, SD3 = 50 kg seed 750 m^{-2}, SD4 = 50 kg seed 1,000 m^{-2}.
Source: Hong (1995).

because of continued physiological activities than in seedlings with lower tissue N content (Table 5; Hong 1995). Farmers can harvest an additional 2 t ha^{-1} with semidwarf varieties under flash-flood conditions by making a small additional investment in applying N fertilizer in the seedbed about 10–15 days before transplanting as well as by other nursery management practices (Hong 1995).

In the flood-prone deepwater rice-growing areas of West Bengal, India, the cultivation of dry-season (boro) rice has become common during the last decade. Boro rice is usually transplanted in January and harvested between the end of April and mid-May. The standing boro crop, however, prevents seeding of wet-season deepwater rice in April/May. This results in either delayed sowing or a foregone wet-season rice crop. The grain yield of boro rice is an assured 4–5 t ha^{-1} compared with an uncertain 1.0–1.5 t ha^{-1} for wet-season deepwater rice. So, farmers normally sacrifice growing deepwater rice (Bardhan Roy and Chakraborty 1995).

Innovative farmers, however, have started growing both boro and deepwater rice by adjusting the establishment technique. One such technique involves sowing boro rice varieties IET 826, IET 1444, and IR36 in a seedbed in late November/early December. Boro rice seedlings (40–50 days old) are transplanted in mid-January in well-prepared land fertilized with diammonium phosphate (200 kg ha^{-1}) and muriate of potash (70 kg ha^{-1}). Urea at 140 kg ha^{-1} is applied at 30 and 60 days after transplanting. Before transplanting boro, freshly harvested seeds of photoperiod-sensitive

Table 4. Yield[a] and yield components[a] of rice as influenced by seeding density, seedling age, and nitrogen application in the seedbed.

Seedling density[b]	Seedling age				
	40 days		20 days		Mean
	N application (kg ha^{-1})		N application (kg ha^{-1})		
	0	15	0	15	
	No. of panicles m^{-2}				
SD1	386 b	408 a	369 a	367 a	382 a
SD2	428 a	385 a	376 a	376 a	391 a
SD3	405 ab	380 a	357 a	352 a	373 a
SD4	382 b	378 a	346 a	349 a	363 a
	No. of filled grains panicle^{-1}				
SD1	54 a	55 a	68 a	71 b	62.1 c
SD2	59 a	62 a	66 a	64 c	62.9 bc
SD3	57 a	64 a	76 a	78 a	68.4 a
SD4	61 a	64 a	70 a	75 ab	67.7 ab
	1,000-grain weight (g)				
SD1	21.8 a	21.3 a	22.6 a	22.1 a	21.9 a
SD2	21.5 a	21.1 a	22.7 a	22.5 a	21.9 a
SD3	22.1 a	22.1 a	22.3 a	22.8 a	22.3 a
SD4	20.9 a	21.4 a	22.5 a	23.4 a	22.0 a
	Grain yield (t ha^{-1})				
SD1	4.51 a	4.62 b	5.58 bc	5.35 b	5.01 b
SD2	5.01 a	4.97 ab	6.04 ab	5.99 a	5.50 a
SD3	5.18 a	5.33 a	6.22 a	6.24 a	5.74 a
SD4	4.52 a	4.71 a	5.36 c	5.68 ab	5.06 b

[a] Within each days after transplanting, means in a column followed by a common letter are not significantly different at the 5% level by Duncan's multiple range test. [b] SD1 = 50 kg seed 250 m^{-2}, SD2 = 50 kg seed 500 m^{-2}, SD3 = 50 kg seed 750 m^{-2}, SD4 = 50 kg seed 1,000 m^{-2}.
Source: Hong (1995).

traditional deepwater rice varieties, such as Hatipajra, Amol, Raktapanikalash, and Kamouth, are broadcast at 70–90 kg ha^{-1} and incorporated into the soil during puddling for the boro-season crop. They remain dormant for a considerable time. Mature boro rice is harvested by the end of April. With the onset of the premonsoon rain, seeds incorporated into the soil during puddling for boro rice start to appear 30–35 days after the boro harvest. Germination is about 60–70% and the seedlings are 20–25 cm tall with 1–2 tillers plant^{-1} after 1 month. At this time, there is no accumulation of floodwater; the nitrogen is applied at 70 kg ha^{-1} at 45 days. This establishment method allows farmers to harvest 5–6.8 t ha^{-1} of rice per year, with deepwater rice contributing 25–36% of the total production.

Table 5. Plant mortality (%) as affected by nursery and transplanting management.[a]

Management	Plant mortality (%)
Seedling age at transplanting	
30 d	22.2 a
20 d	12.9 b
Nitrogen applied in the nursery	
1 wk before uprooting seedlings	23.8 a
2 wk before uprooting seedlings	11.3 b
Transplanting done	
Within 6 h after uprooting	25.9 a
Within 18 h after uprooting	18.7 a
Within 30 h after uprooting	8.0 b

[a] Means of four replicates. While awaiting transplanting, seedlings were kept in freshwater under shade.
Source: Unpublished data, Hong (2000).

Submergence generally affects crop establishment more seriously than other crop performance factors. The solution rests in modifying nursery management and "hardening" the seedlings prior to transplanting. The opportunities for this are greater when medium (130-day-old) to mid-late-maturity (140–150-day-old) cultivars are chosen.

Nursery management

Nursery management practices, especially seeding density and fertilizer application, can alter the quality of seedlings in the seedbed, which directly affect the growth and yield of transplanted rice. Greenhouse and field experimental results show that the seeding density in the seedbed significantly reduced the height of rice that was transplanted using 40-day-old seedlings (DOS) but did not influence the height of rice when seedlings were fertilized in the nursery with nitrogen and transplanted at 20 days after sowing (DAS). Transplanted rice that used 40 DOS also had a lower leaf area index (LAI) than that which used 20 DOS. Plants transplanted at 40 DAS also produced more panicles, but their panicles were smaller, had fewer filled grains, and low grain weight and therefore low grain yield (Table 4). Seedling age, on the other hand, did not greatly alter the yield of rice when crops were transplanted on time, but, for late planting, older seedlings were better (Reddy et al 1987).

Higher seeding density in the seedbed (at 50 kg seed per 250 m^2) resulted in a lower number of tillers as well as LAI in the first 4 weeks after transplanting. Rice transplanted using 20 or 40 DOS had the highest LAI values at the flowering stage. Nitrogen application in the seedbed did not influence LAI after transplanting. Higher seeding density in the seedbed delayed the flowering and maturity of transplanted rice. Plants that were transplanted at 40 DAS matured 7 days earlier but had 13 days' longer total growth duration than those transplanted at 20 DAS (Hong 1995).

Plants transplanted at an early age (12 and 15 DAS) had a longer recovery period and higher survival percentage under submergence than those transplanted at a later age (18 and 21 DAS). Plants fertilized with nitrogen at 12 and 8 days before transplanting (DBT) also had a higher survival percentage under submergence than those fertilized at 4 DBT and the unfertilized plants (Hong 1995).

Plants having shorter height before submergence had a higher percent increase in height during submergence. This increase in plant height was attributed to rapid elongation of the leaf sheath rather than the leaf blade (Hong 1995).

Seedling management

Conditioning of seedlings. The root system of rice seedlings, even when raised under the wetbed method of nursery, usually grows under oxidized soil conditions and faces reduced soil conditions when a considerable amount of oxygen is used in oxidizing the reduced soil surrounding the seedling roots in the process of transplanting/establishment in the puddled main field. The rice leaves (in the seedling) transport the oxygen. The longer the root, the greater is its oxygen requirement. Resultant competition for oxygen between the need for soil oxidation and root respiration delays the emergence of new roots that are much needed for adequate anchorage and plant establishment. The uptake of water and nutrients is also delayed/slowed as a consequence. When seedlings are not well handled (crushed leaves, etc.), oxygen transport is further slowed, thus delaying seedling establishment. Meanwhile, seedling leaves continue to transpire, thus placing a demand on water, which, if not met adequately, causes the transplanted seedlings to often wither in spite of their being placed in a submerged soil. The larger the leaf surface, the more transpiration there is and demand is greater for water uptake. This "transplanting shock" felt by plants in transition from the nursery to main fields is less serious when not compounded by other stresses. However, should flooding occur before the seedlings recover from this shock, crop survival and growth are seriously affected.

It is therefore advisable to keep the seedlings in fresh (running) water for 24–36 hours and also to detop two-thirds of the leaf length (to reduce transpiration) before transplanting. Such a practice leads to better and faster plant establishment. Newly formed roots that emerge while kept in running water and the reduced leaf area caused by detopping contribute to better survival. Such seedlings have a higher survival even under 9 days of submergence and also give a higher grain yield because of their greater plant population (Tables 5 and 6).

Root pruning. Root pruning before transplanting, leaving only 2- to 5-cm length from an initial length of 13.5 cm and 25.7 cm for the 18- and 25-day-old seedlings, has consistently been shown to give higher plant height up to 40 DAT and more tillers, LAI, shoot biomass, and grain yield because of more panicles than the control (uncut roots). Root pruning had no effect on root length after 10 DAT and on root biomass (Table 7).

Too much pruning of roots, leaving only 1 cm before transplanting, significantly reduced plant height and shoot and root biomass. Plants fertilized with nitrogen at 12 and 8 DBT had a higher soluble sugar content in the leaf blade and leaf

Table 6. Effect of seedling management on rice performance in flood-prone environments.

Seedling management	Recovery from transplanting (d)	Survival^a (%) after 9 days of submergence^b	Root biomass (g plant^{-1}) at 40 DAT	Root biomass (g plant^{-1}) at 40 DAT	Grain yield (t ha^{-1})^c
Seedlings kept in running water for 24–36 h before transplanting					
2/3 of leaf length detopped	3	92 d	35.0 a	4.4 a	2.1 b
Leaves not detopped	4	80 c	34.8 a	4.4 a	1.8 b
Seedlings transplanted immediately after pulling					
2/3 of leaf length detopped	4	67 b	34.7 a	4.4 a	1.1 a
Leaves not detopped	3	58 a	34.3 a	4.3 a	0.8 a

[a]Means in a column followed by the same letter are significantly different at 0.05 by Duncan's multiple range test. [b]Submerged 5 days after transplanting (DAT). [c]Field data; mean of two years.
Source: Unpublished data, Singh (1999 and 2000).

Table 7. Influence of root pruning on different agronomic characteristics of rice.[a]

Root length (cm)	Plant height (cm)	No. of tillers hill^{-1}	Leaf area index (cm^2 plant^{-1})	Root length (g plant^{-1})	Root biomass (g plant^{-1})	Shoot biomass (g plant^{-1})	Grain yield (g plant^{-1})
0.5	115.0 a	28.0 c	3,663 b	36 a	5.0 b	58.6 b	67.0 b
2.0	117.0 a	38.0 a	4,471 a	40 a	7.4 a	87.6 a	76.5 a
5.0	116.0 a	36.0 ab	4,233 ab	36 a	7.3 a	86.6 a	77.1 a
Control	119.0 a	33.0 b	4,097 ab	36 a	6.8 a	77.4 a	73.9 a

[a] Taken at 30 days after transplanting (DAT), all other parameters at 60 DAT or later. All values are means for the data from 18- and 25-day old seedlings used at transplanting.
Source: Unpublished data, Hong (2000).

sheath than those fertilized at 4 DBT and the control. In contrast, plants transplanted in N-fertilized trays had a lower soluble sugar content than those transplanted without fertilizer (Hong 1995).

Double transplanting of seedlings. Rice farmers in flood-prone areas use a traditional system of “double transplanting” (3- + 4-week-old seedlings) in which they transplant 3-week-old seedlings and let them grow for 4 weeks. They uproot the 4-week-old transplanted crop and again retransplant it. This practice was evaluated in farmers' fields in Bahraich District of Uttar Pradesh and compared with the farmers' other options—namely, (1) direct seeding with the onset of monsoon, (2) transplanting of older (7-week-old) seedlings, and (3) transplanting of a short-duration postflood rice crop.

The practice of “double transplanting” ensures getting a decent crop in flash-flood areas where crop damage is severe (Table 8). Rice yields in this system are

Table 8. Grain yield as affected by postflood management.

Treatment	Grain yield (t ha^{-1})		
	Ghagharagat	Tiwari Purwa	Bhupani
Farmers' practice (direct seeding)	2.89 1 Jul	2.14 10 Jul	2.10 10 Jul
Transplanting (7-wk-old seedlings)	2.43 7 Aug	2.04 16 Aug	1.99 18 Aug
Double transplanting (3- + 4-wk-old seedlings)	2.30 7 Aug	2.77 17 Aug	2.48 19 Aug
Transplanting (short-duration— NDR97— variety)	1.90 29 Aug	1.63 30 Aug	1.23 3 Sep

Source: Unpublished data, Dwivedi (2000).

higher than with direct seeding (which is possible only in good years), transplanting of older seedlings, and raising a postflood short-duration transplanted crop. Results also indicate that direct seeding is a better practice than transplanting of older seedlings.

Use of clonal tillers

Another innovative approach could be transplanting with tillers removed from the long-duration, photosensitive semidwarf to semitall varieties, as has been explored through several field studies at CRRI. Removal of some of the clonal tillers (100–130 m^{-2}) from early sown crops (by the end of May) with a 50% higher seed rate (600 seeds m^{-2}) after 40–80 days of growth for planting on an equivalent area did not cause any adverse effect on the performance of the mother crop (Table 9) (Sharma 1992a,b, 1994b, 1995). Similarly, when half the tillers were removed from a 20–40-day-old transplanted crop, yield did not decrease (Reddy and Panda 1988). The loss in tiller number caused by their removal was recovered partially after some time because of the long vegetative phase of the crop. A slight decrease in panicles m^{-2} at maturity in the mother crop caused by the removal of clonal tillers was compensated for by the resultant increase in panicle weight; yield ultimately showed no difference when compared with that of the undisturbed crop.

The clonal tillers were taller and had more dry weight than the conventional nursery seedlings of equal age. Therefore, the clonally propagated crop established well and acclimatized faster in the similar flooded environment compared with the nursery seedlings, which did not establish properly as they had been previously growing in an aerobic upland environment. Therefore, the grain yield of the crop was significantly higher when transplanted from clonal tillers than from nursery seedlings (Sharma 1994b).

Table 9. Effects of different dates of sowing and transplanting on growth and yield attributes of rice under intermediate deepwater conditions in 1991.

Treatment	Plant height (cm)		Tillers m^{-2} on 21 Sep	Panicles m^{-2}	Panicle weight (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})
	21 Sep	Maturity					
Direct sowing[a]							
10 May	140	157	185	156	2.48	3.15	9.30
20 May	136	163	151	127	2.99	3.19	9.23
30 May							
400 seeds m^{-2}	143	159	188	166	2.48	3.42	9.47
600 seeds m^{-2} (a)	138	154	158	134	2.84	3.19	7.33
600 seeds m^{-2} (b)	135	156	163	143	2.74	3.32	7.60
600 seeds m^{-2} (c)	139	153	159	135	2.64	3.19	7.16
10 June							
400 seeds m^{-2}	135	150	162	119	2.39	3.03	6.53
600 seeds m^{-2} and 60 kg N ha^{-1}	145	152	170	128	2.32	3.20	7.20
20 June							
400 seeds m^{-2}	130	158	127	118	2.12	2.20	6.70
600 seeds m^{-2} and 60 kg N ha^{-1}	134	156	128	122	2.21	2.45	6.67
30 June							
400 seeds m^{-2}	103	132	102	100	2.08	2.28	5.20
600 seeds m^{-2} and 60 kg N ha^{-1}	108	134	111	105	2.18	2.41	5.77
Transplanting							
25 July							
Unfertilized nursery seedlings	76	0	3	0	0	0	0
Fertilized nursery seedlings	87	109	30	19	1.95	0.19	1.15
Clonal tillers uprooted from (a)	99	121	69	47	2.45	1.16	3.27
5 August							
Unfertilized nursery seedlings	79	105	20	45	1.49	0.37	0.50
Fertilized nursery seedlings	88	111	68	51	1.91	0.64	2.07
Clonal tillers uprooted from (b)	108	136	109	84	2.76	1.92	4.60
15 August							
Unfertilized nursery seedlings	75	97	16	14	1.58	0.32	1.15
Fertilized nursery seedlings	85	107	26	24	2.26	0.78	2.15
Clonal tillers uprooted from (c)	113	135	69	75	2.62	1.64	4.20
S.E.	2.4	3.8	6.9	7.5	0.109	0.136	0.448

[a] Sowing was done with 400 seeds m^{-2} and 40 kg N ha^{-1} wherever not specified.

Source: Sharma (1994b).

It is therefore evident that direct seeding of rice may be preferred to transplanting in the flood-prone lowlands for achieving a reasonable and assured productivity. Sowing time should be chosen so that plants are about 1 month old before they experience complete submergence. In areas where direct seeding on time is not possible because of weather-related or physical constraints, transplanting with healthy, vigorous seedlings fertilized in the nursery or tillers uprooted from previously established direct-seeded crops may be practiced. Assuming a seedling emergence of 40–50% for the crops sown with 400–600 seeds m^{-2}, a stand with about 240–300 plants m^{-2} can be expected even under subnormal conditions by 40–50 days of growth. About one-third of these plants can be uprooted for use as seedlings for transplanting on an equivalent area, without causing any adverse effect on the performance of the mother crop. This practice can also be employed for covering the wide unfilled gaps in flood-damaged crops by splitting tillers from the remaining surviving plants as a mid-season corrective measure to improve productivity. Therefore, this practice is also relevant when early floods have partially damaged a crop and nursery seedlings are not available for late transplanting.

Summary and conclusions

The flood-prone environments occupy a significant extent of rice lands in South and Southeast Asia. Millions of subsistence farmers and their families depend on production from these lands for their livelihood. Although rice productivity in these environments is low, they contribute substantially to the total rice supply. Their lower productivity is primarily a result of adverse hydrological conditions. The problems of rice crop submergence are acute at the time of crop establishment.

Using appropriate cultivars and timely crop establishment through direct seeding or transplanting are crucial operations for improving crop productivity. In situations where transplanting is the option for crop establishment, special attention has to be paid to nursery and seedling management in order to produce healthy, tall (high vigor) seedlings, which can anchor firmly and adequately withstand submergence. If direct seeding is to be followed, timely seeding at proper depths and uniform germination are to be assured for even stand establishment prior to floodwater accumulation. If crop establishment problems can be overcome, flood-prone environments have high potential for increased rice productivity.

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Notes

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Crop establishment in the flood-prone ecosystem

A.R. Gomosta

This paper discusses the importance of crop establishment of long-term flood-prone deepwater rice (DWR) and short-term flash-flood-prone rainfed lowland rice. In addition, dry broadcast seeding for establishment in the field and crop establishment through ratooning and transplanting of DWR seedlings after the boro harvest are discussed. Both establishment methods can add to production of the normal boro crop. Ratooning of DWR can be accomplished by transplanting DWR seedlings in the boro crop. Therefore, attempts should be made to develop a DWR ideotype that possesses a modern plant architecture, better elongation ability, vigorous ratoon ability, and strong photosensitivity. This will ensure bumper production in the flood-prone boro area, which was previously dominated by DWR before the introduction of irrigated modern rice. Rainfed lowland rice, transplanted in low-lying areas, is often submerged by flash flood. Flash-flood submergence reduces stand density by damaging the plants. The factors that affect submergence tolerance are the determining agent for crop stand. Among them, variety, plant structure, and flooding criteria are important. Among different mechanisms of adaptation, recovery growth during the postsubmergence period is considered to be reestablishment of the crop after flash-flood damage. Recovery growth during the postsubmergence period is determined by variety, recovery period before submergence, time of submergence, and time of N fertilization during the postsubmergence period. Tillering as an indicator of regrowth during the postsubmergence period progressively increases with the increase in recovery period before submergence. However, a tolerant variety regrows faster than a nontolerant variety. In the receding floodwater in medium highland phase 2, farmers usually transplant local T. aman varieties. In these areas, modern high-yielding photosensitive varieties such as BR22 and BR23 are suggested for establishment in place of local T. aman varieties.

Crop establishment refers to the planting methods for obtaining good stand density of the crop to achieve higher productivity. In the flood-prone ecosystem, the quality of crop establishment will depend on climatic and edaphic factors, plant biology, and hydrology of the system. Deepwater rice (DWR) and flash-flood-prone and submergence-prone rainfed lowland rice are the major components of the flood-prone ecosystem. In addition, areas under medium highland phase 2, where floodwater rises to 90 cm and recedes in late September or early October, are also a potential component of the system.

DWR and rainfed lowland rice frequently interact with flooding criteria, which ultimately determine the stand density of the crop. Plant physiological criteria such as nodal tillering in DWR, quick recovery growth of varieties submerged by flash flood, and strong photoperiod sensitivity of the varieties used in the areas under medium highland phase 2 contribute remarkably to the establishment of a good crop for achieving higher productivity in the target environment. This paper discusses the aspects related to crop establishment for achieving more yield in fragile environments such as the flood-prone ecosystem.

Deepwater rice

Deepwater rice is defined as rice that is usually flooded deeper than 50 cm for 1 month or longer during the growing season (Catling et al 1988). In addition, flooding must be sustained for at least 1 month. The definition encompasses all water depths above 50 cm, but there is commonly a distinction between DWR and floating rice. Floating rice grows in more than 100-cm water depth. The cultivars have a strong elongation capacity of 5 to 8 cm d^{-1}. However, traditional floating rice varieties can even have an elongation rate of 25 cm d^{-1} (Choudhury and Zaman 1970).

Planting methods

Under normal conditions, seeds are dry-broadcast. If continuous rain prohibits normal land preparation, the land is puddled and germinated seeds are broadcast. If there is a chance of early flooding, seedlings are transplanted in the puddled soil. A transplanted crop usually yields 50% less than a broadcast crop (Alim et al 1962). The seed is broadcast in April and transplanting cannot be practiced earlier than the first part of June, when flood usually appears. So, before the advent of flood, the broadcast crop completes the development of basal tillers but the transplanted one can hardly get a stand in the field. Thus, the broadcast crop can resist the aggression of floodwater better than the transplanted crop and this accounts for the comparatively higher yield of the broadcast crop. However, our experience with the performance of broadcast and transplanted fields is different. Establishment of the crop stand by broadcasting or transplanting after the boro harvest depends on the advent of floodwater. At Habiganj, when sprouted seeds of BR224 were broadcast and seedlings of 15, 25, and 35 days were transplanted, the crop was not properly established in broadcasting, but the transplanted crop produced around 1 t of rice yield when the field was inundated at 15 days after transplanting (DAT) or 15 days after sowing (DAS) (Table 1). Grain yield decreased, however, with the decrease in seedling age. Seedlings originated from sprouted seeds could not thrive in the early flooding.

Table 1. Yield and yield components of BR224 when different-aged seedlings were transplanted and sprouted seeds were broadcast.

Treatment/ seedling age (d)	Grain yield[a] (t ha^{-1})	Panicles (no. m^2)	1,000-grain wt (g)	Filled grains per panicle
35	1.70 a	148 a	2.56 a	80
25	1.68 a	130 a	2.57 a	80
15	1.01 b	84 b	2.46 a	87
Sprouted	0.21 c	26 c	2.42 a	65

[a]In a column, values followed by the same letter are not significantly different by Duncan's multiple range test. Source: Annual report, BRRI (1990).

Table 2. Yield and yield components of deepwater rice as affected by four different plant densities.

Initial density (m^2)	Preflood tillers[a] (no.)	Tillers at peak flood (no.)	Panicles (no.)	Panicles weight (g)	Filled grains (no.)	1,000-grain weight (g)	Yield (t ha^{-1})
50	1,082.0**	549.61**	2,366.0	9.86	380.9	1.6	1.6
100	6,018.0**	133.71**	1,674.9	0.02	32.7	2.2	0.1
200	5,967.5**	282.71**	403.0	2.46	4.2	0.0	0.9
350	3,731.5**	1,513.71**	2,822.9	0.16	104.7	2.9	3.6
X^2	2.0 ns	4.1 ns	2.0 ns	17.77**	10.5*	6.2 ns	6.8 ns

[a]** = significant at the 1% level, * = significant at the 5% level, ns = not significant.
Source: Hoque and Nasiruddin (1988).

Stand establishment

Importance. Although stand establishment has an obvious relationship with eventual grain yield, surprisingly few studies are available on this aspect. Because of the long growth duration of DWR, the crop stand varies because of the addition of nodal tillers or loss of basal tillers because of submergence or pest attack. As a result, some workers obtained a good relationship between initial stand and grain yield while some failed to obtain that. Hoque and Nasiruddin (1988) concluded that initial seedling densities ranging from 50 to 350 plants m^{-2} had little effect on optimum yield level (Table 2). On the contrary, we observed an increase in grain yield with an increase in initial stand (Table 3). However, such a relationship may be jeopardized by the abnormal rise of floodwater.

Fluctuation of crop stand. Our studies revealed that the initial stand of dry-seeded DWR varieties decreases at two major points: seedling emergence and initial inundation. Fifteen local varieties were dry-seeded at 90 kg ha^{-1} to identify the major limiting points for the reduction in potential seedling stand. The mean potential seed-

Table 3. Yield and yield components of Hbj A IV as affected by initial stand density.

Initial stand (tillers m^{-2})	NP/BP[a]	Panicle length (cm)		Panicles (no. m^{-2})[b]	Filled grains (no. panicle^{-1})	Grain yield (t ha^{-1})
		Basal	Nodal			
25	11/20	22.8	19.3	89 c	125 a	1.51 c
144	5/20	22.4	17.3	110 b	97 b	1.95 b
296	1/20	21.0	16.0	191 a	73 c	2.60 a

[a]NP = panicles from nodal tillers, BP = panicles from basal tillers. [b]In a column, values followed by the same letter are not significantly different by Duncan's multiple range test.
Source: Annual internal review (1990).

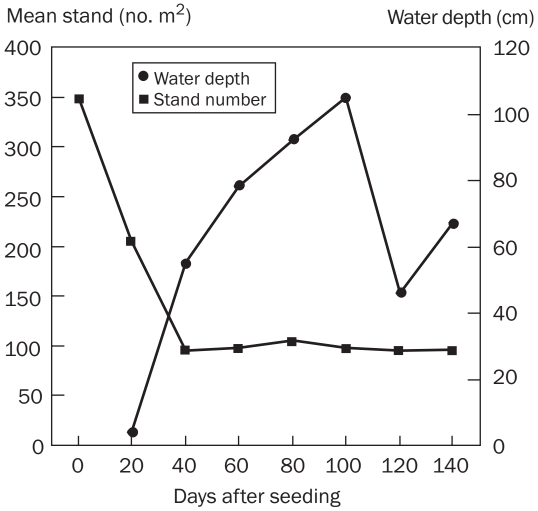

Fig. 1. Mean stand number of 15 deepwater rice varieties at different days after seeding.

ling stand was more than 300 m^{-2}, declining to 200 at the seedling emergence stage. This decreased further to 100 seedlings m^{-2} when the crop field was inundated by 50-cm water depth at 40 DAS (Fig. 1). After that, the plant population did not decrease even when the water depth reached 1 m. The percentage of initial stand reduction varied from 36% to 60% among varieties.

Detailed information on stand density throughout the vegetative phase was recorded for three consecutive years in Agrakhola, Bangladesh (Catling et al 1982). The observations indicated that the fluctuation in crop stand was a consequence of early drought or later surge of flooding or the early rise of floodwater when many young tillers failed to cope.

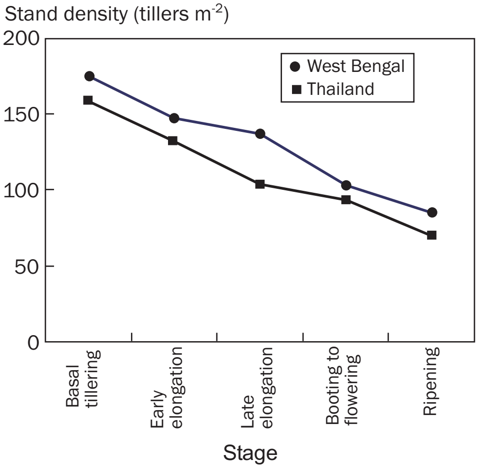

Fig. 2. Stand density of deepwater rice at different growth stages of the crop (adapted from Catling 1992).

Compensation of crop stand. Reduction in crop stand at the early stage is compensated by vigorous basal tillering. The highest-tillering population is usually observed just before flooding. Throughout the flooding period, stems are continuously lost by submergence (Fig. 2). Nodal tillering is a unique character of DWR, which can partly offset this loss. Nodal tillering also compensates for sparse stands resulting from drought or flash floods and for stem damage caused by stem borers and rats (Catling et al 1987).

We observed a strong negative association between degree of basal tiller damage and the production of nodal tillers in a pruning experiment in the field (Fig. 3A, 3B). This confirms the finding of Catling and Islam (1979) on the formation of nodal tillers in stem borer-damaged DWR. De Datta and Banerjee (1979) also observed a higher number of nodal tillers when basal tillers were reduced by submergence in Jaladhi I and Jaladhi II. Thus, nodal tillering ability of DWR is an adaptive and important trait that can be advantageous after droughts, insect attacks, and flash floods that reduce stand density. The higher production of nodal tillers in the case of a lower density of basal tillers was also observed in other experiments (Table 4).

Variable reports on the contribution of nodal tillers to grain yield are available. Some researchers estimated a 1% contribution and De Datta and Banerjee (1979) found a 22% to 47% contribution to grain yield. We reported that the contribution of nodal tiller panicles to grain yield depends on the degree of loss of basal tillers. The contribution of nodal tiller panicles to grain yield varied from 6% to 7% when there was no loss of basal tillers. This rose to 40% to 48% when basal tillers were clipped by 75% (Fig. 4).

Nodal tiller panicles were short and had fewer spikelets than corresponding basal tiller panicles (Table 5). However, basal and nodal tiller panicles produced

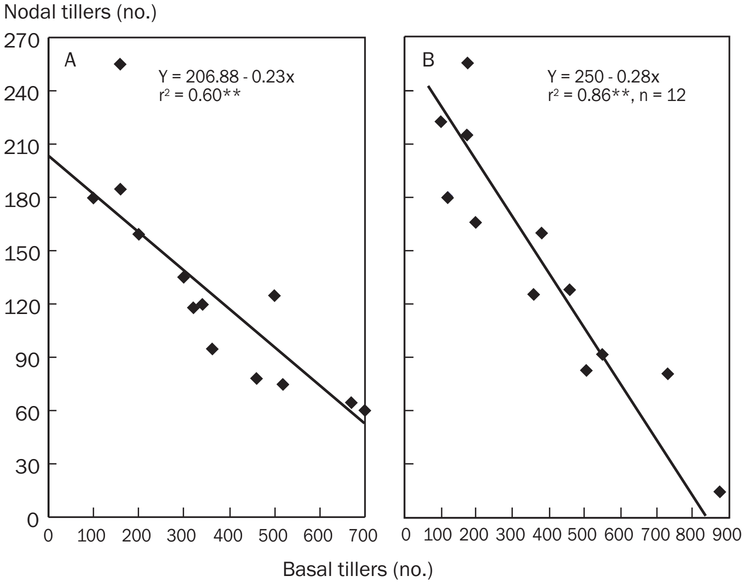

Fig. 3. Nodal tillering in relation to basal tillers per unit area in Habiganj Aman I (A) and Habiganj Aman VIII (B) (adapted from Gomosta et al 1982).

Table 4. Tillering behavior of Habiganj Aman I and Habiganj Aman VIII as affected by application of urea.

Treatment	Basal tillers plant^{-1}			Nodal tillers per plant
	Before submergence[a]	After submergence	Survival (%)	
Habiganj Aman I				
Control	11.0 b	8.0 b	73	3.2
With urea	27.8 a	18.0 a	65	1.4
Habiganj Aman VIII				
Control	10.4 b	8.8 b	5	6.4
With urea	35.4 a	21.8 a	62	2.8

[a] In a column, values followed by the same letter are not significantly different by Duncan's multiple range test. Source: Gomosta et al (1982).

spikelets in most of the clipping treatments. Thus, in addition to compensation in the number of nodal tillers, DWR in this study also compensated with a higher number of spikelets per panicle when the number of basal tillers decreased. These compensating processes in DWR explain how grain yield can be similar at different stem densities.

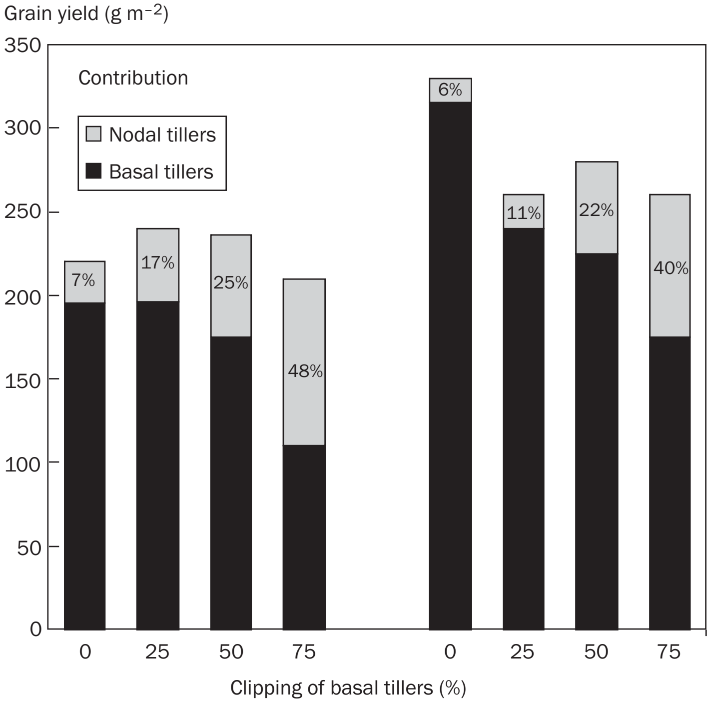

Fig. 4. Percentage of contribution of nodal tillers to grain yield as affected by basal tiller clipping (International Deepwater Rice Workshop, 1981).

Stand establishment other than the traditional method

The usual method of crop establishment is direct sowing (broadcast) with the first good rains following land preparation. In dry years, the crop is sometimes sown dry into the soil and seed germinates when sufficient rainfall occurs. In years of heavy early rains, some farmers puddle their fields and sow pregerminated seed. Another method is to sow presoaked seed on once-plowed land and then cover it by plowing or laddering.

Under special circumstances, farmers adopt some crop establishment methods that are not very common but appear promising. In a few fields in Faridpur and Sylhet districts, seeds were dibbled (Talukder and Alam 1982-85) and in Tangail District seedlings were dibbled into 15 cm of water following a boro crop (BRRI-ODA 1988).

Among the alternative methods of crop establishment, both ratooning and transplanting of deepwater rice seedlings after the boro harvest appear to be promising. Both establishment methods can add production to the normal boro crop. Ratooning or transplanting of deepwater rice has the potential to fill up a large water body, which usually remains fallow during the flooded period.

Ratooning of the crop. Many DWR crops produce ratoon vigorously (Chauhan et al 1985, Bene 1988a). DWR planted at the start of the dry season (November-

Table 5. Effect of basal-tiller clipping on panicle production of Habiganj Aman I and Habiganj Aman VIII.

Basal tiller pruning	Basal panicles (no. m^{-2})	Basal tiller panicles (no. m^{-2})	Basal tiller panicles (%)	Nodal tiller panicles m^{-2}	Total no. of panicles m^{-2}	Panicle length (cm)		Spikelets per panicle	
						Basal tiller	Nodal tiller	Basal tiller	Nodal tiller
Habiganj Aman I									
Control	165	120	72	11	131	24	20	166	134
25%	122	85	70	21	106	23	21	177	145
50%	82	66	80	26	92	23	20	160	146
75%	41	34	83	45	79	24	22	180	165
Habiganj Aman VIII									
Control	192	116	61	13	129	24	20	147	119
25%	148	93	63	19	111	24	21	164	110
50%	95	81	85	34	115	25	22	175	118
75%	47	40	85	52	92	24	22	160	112
LSD (5%)	–	12.9	–	11.6	15.8	–	1.6	–	–
LSD (1%)	–	17.9	–	16.1	21.7	–	2.2	–	–

Source: Gomosta et al (1982).

Table 6. Grain yield as affected by ratooning of Hbj A IV.

Treatments[a]	Grain yield (t ha^{-1})			
	Boro season		DWR season	
	Boro rice	DWR	Normal DWR	Ratoon DWR
DWR alone transplanted in boro season	–	3.2	–	2.4
DWR alone broadcast in DWR season	–	–	2.5	–
DWR alone transplanted in DWR season	–	–	2.6	–

[a] DWR = deepwater rice.
Source: Rashid et al (1988).

December) flowers in late March or early April because of its strong photoperiod sensitivity and produces a crop in April or May. When cut back, a ratoon crop is regenerated and grows throughout the flood season and flowers and ripens at the same time as a normal DWR. DWR ratooning appears to be a potential system for double cropping in deeply flooded areas. DWR ratoons require less water to establish and no land preparation is necessary.

At Chinsurah, West Bengal, India, there were no differences in yielding ability of the normal DWR crop and ratoon crop (Roy et al 1988). In fact, the ratoon crop sometimes produced taller plants and a greater tiller number and panicle size. In Bangladesh, also, little difference between the normal DWR crop and ratoon crop was reported (Rashid et al 1988, Table 6).

Ratooning of DWR can be accomplished by transplanting DWR seedlings in the boro crop at the transplanting stage. In Bangladesh, some farmers are reported to mix DWR boro seeds in the proportion of 1:5 to 1:7 in the nursery, which then grow as a normal boro; after harvest, the DWR is ratooned. Another approach is to transplant boro and DWR in a 3:1 hill pattern at 20 × 20-cm spacing with the normal fertilizer rate for a boro crop (Bene 1988b). The boro crop is harvested first along with DWR plants at 15 cm above the soil and immediately topdressed with 30 kg N ha^{-1}, with no cultivation. Ratoon growth in DWR starts immediately, thus producing a second rice crop.

Considering the above points, attempts should be made to develop a DWR ideotype having modern plant architecture, better elongation ability, vigorous ratoon ability, and strong photosensitivity. This will ensure higher production in the flood-prone boro area, which was previously dominated by DWR before the introduction of irrigated modern rice.

Transplanting of deepwater rice. While crop establishment can be accomplished by ratooning of DWR through intercropping in the boro rice field, relay cropping of DWR by transplanting seedlings or broadcasting sprouted seeds after the boro harvest is another method of crop establishment. In Bangladesh, transplanting of floating rice following a boro crop was observed by Bramer as early as 1960 (Catling

1992). Sen (1975) mentioned this as a new practice. Talukdar and Alam's studies (1982-85) revealed that 3% to 4% of the fields were transplanted in Sylhet, Faridpur, and Dhaka, whereas 28% of the fields were transplanted in Tangail, Mymensingh, and Jamalpur with DWR.

A significant portion of DWR in the 50–100-cm depth class is transplanted. In general, the method of growing seedlings and land preparation is similar to that of rainfed lowland and irrigated rice culture. However, DWR seedlings need to be tall to survive the first surge of flooding and to have more leaves above water. Tallness is usually achieved by growing the seedlings longer in the nursery bed. The seedlings must have a minimum period of 2 weeks of recovery after transplanting so that the plants can elongate strongly in rising water. The hills may be closely spaced (15 × 15 or 15 × 20 cm) or widely spaced (25 × 25 cm). They are usually planted with many seedlings per hill (3–4) to compensate for the preflood-period basal tillering.

In 1976-77, the BRRI Adaptive Research Division established the DWR crop as a relay or succession crop in boro fields by transplanting DWR seedlings after the boro harvest or broadcasting sprouted seeds in the standing boro crop. According to this experience, the principal factors responsible for the success of their methods may be timing of the flood, variety, and date of planting of the boro crop. Flooding after proper establishment of DWR is preferable for a good harvest of this crop under these cultivars.

It is obvious that transplanted DWR crop establishment will not be possible if the plants are not properly established after transplanting because of early flood or prolonged drought. Considering this problem, we tested the elongation ability of transplanted DWR plants without a recovery period in rising floodwater. The test involved 35-day-old transplanted seedlings and allowed a 2-week recovery period before floodwater inundation; another set of plants contained 50-day-old seedlings inundated in water immediately after transplanting. The rate of floodwater rise was slow or rapid. The results indicated that the internodes of aged seedlings of DWR plants that did not experience a recovery period after transplanting can elongate successfully in rising water when the water depth increases slowly (Fig. 5).

Rainfed lowland rice

Rainfed lowland rice that is transplanted in low-lying areas is often submerged by flash flood. The water depth varies from 50 to 100 cm and duration of flooding is usually 10 to 15 days. The water body is usually turbid. Flash-flood submergence reduces stand density by damaging the plants. Tolerance of the plants for submergence depends on factors such as variety, seedling criteria, flooding criteria, etc. The crop may be inundated by floodwater immediately after transplanting or at the early tillering stage or at mid-tillering during late flooding.

Factors affecting submergence tolerance

Factors that affect submergence tolerance are the determining agents for crop stand. Among them, plant varietal factors and flooding criteria are important.

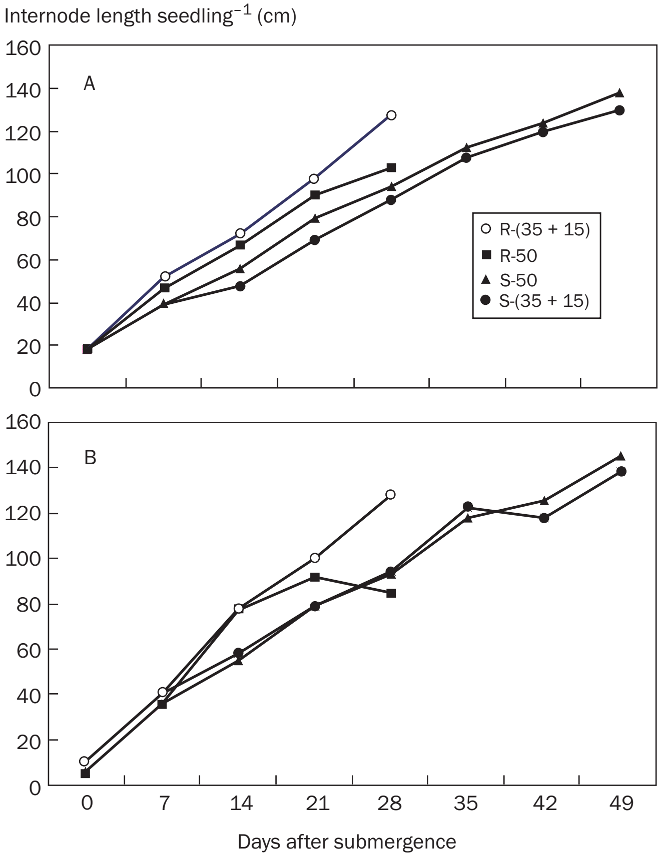

Fig. 5. Length of elongated internodes of Hbj A I (A) and M. Digha (B) at slow (S) and rapid (R) rise of water depth. The numbers 35 and 50 represent age of seedlings in days, 15 represents a 15-day recovery period.

Variety. Eighteen cooperators tested a uniform set of 12 rice varieties for submergence tolerance using their own methods (Hille Ris Lambers and Vergara 1982). Results varied among test methods but are consistent in identifying FR13A as a submergence-tolerant material because it elongates very little under submergence and thereby loses its reserve CHO slowly under submergence but can maintain chlorophyll stability. On the contrary, BR5, a nontolerant variety, elongates under submergence and loses CHO rapidly and cannot maintain chlorophyll stability.

Seedling criteria. Submergence tolerance is related to seedling criteria such as seedling age, recovery period after transplanting, and quality. Submergence tolerance increases with the increase in seedling age, increase in recovery period after transplanting, and increase in seedling quality (Table 7). It is remarkable that there is

Table 7. Submergence tolerance of five rice varieties as affected by seedling age.

Seedling age (d)	Initial plant ht. (cm)	% Increased ht. (cm)	Dry matter content before submergence (mg seedling^{-1})	Submergence tolerance (score)[a]
FR13A				
40	50.8	28.9	–	1
30	50.6	26.0	620	1
20	40.0	40.0	340	1
10	28.1	53.7	90	1
Pajam II				
40	59.2	48.7	590	1
30	46.3	54.4	360	1
20	38.6	73.5	210	3
10	26.9	81.4	50	9
IR20				
40	37.4	38.2	400	1
30	28.8	67.7	240	5
20	26.5	80.0	120	5
10	20.0	116.0	80	9

[a] On a scale of 19, where 1 = excellent and 9 = very poor.
Source: Annual report, BRRI (1979).

a wide difference in tolerance levels between FR13A and BR3 although they had similar dry matter content in unit length of seedlings.

Flooding criteria. Submergence tolerance of a variety decreases with the increase in depth and duration of submergence (Table 8). Submergence tolerance is also affected by the light environment under water. Plant survival in turbid water is highly reduced compared with that in clear water. In a controlled experiment, where plants were covered with black cloth during submergence, the nontolerant BR5 and BR1 were completely destroyed, whereas the tolerant variety FR13A survived. Under uncovered conditions, all varieties survived when submerged in clear water.

Recovery growth

Recovery growth during the postsubmergence period is very important when stand establishment is completely destroyed by flash-flood submergence. Plant damage at the vegetative stage is the destruction of leaf blades and leaf sheaths. New shoots emerge from the tiny stem at the base of damaged plants during the postsubmergence period. Good recovery growth during the postsubmergence period can be considered as reestablishment of the crop after flash-flood damage.

Recovery growth during the postsubmergence period is determined by variety, recovery period before submergence, time of submergence, and time of N fertilization during the postsubmergence period. Tillering ability as an indicator of regrowth

Table 8. Submergence tolerance of BR4 as affected by recovery period after transplanting and seedling age.

Recovery period (d)	Seedling age (d)	Total plant age (d)	% Elongation of seedling ht. (cm)	Submergence tolerance
10	40	50	96.6	1
	30	40	137.0	5
	20	30	256.9	7
	10	20	340.7	9
5	40	45	13.9	3
	30	34	111.6	5
	20	25	258.2	9
	10	15	200.0	9
0	40	40	7.0	3
	30	30	64.8	7
	20	20	90.7	9
	10	10	117.8	9

[a] On a scale of 19, where 1 = lowest and 9 = highest.
Source: Annual report, BRRI (1979).

Table 9. Submergence tolerance of rice varieties as affected by seedling quality.

Seedling quality	Seedling ht. (cm)	Dry matter		Submergence tolerance (score)[a]
		(mg seed^{-1})	(mg cm^{-1})	
FR13A				
High	63.4	425	67.8	1
Low	26.1	56	21.4	1
BR3				
High	56.4	496	77.9	3
Low	18.9	43	22.9	7
BR4				
High	53.3	277	52.0	4
Low	18.9	53	17.6	9
BR5				
High	63.3	331	52.0	6
Low	20.8	34	16.2	9

[a] On a scale of 19, where 1 = lowest and 9 = highest.
Source: Annual report, BRRI (1980).

during the postsubmergence period progressively increases with the increase in recovery period before submergence (Table 9). However, a tolerant variety regrows faster than a nontolerant variety (Fig. 6). Regrowth and consequently grain yield are much better when N fertilization is done 15 days after the drainage of water than when N is applied immediately after the drainage of water. Among different growth

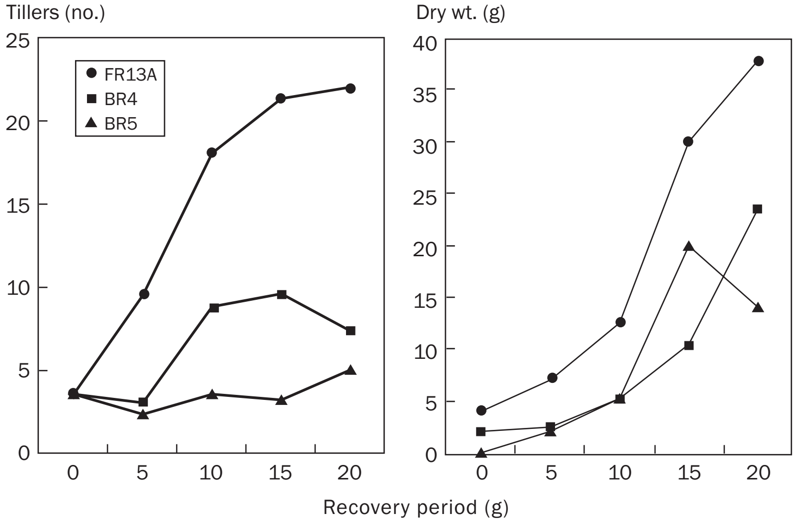

Fig. 6. Tillering potential (A) and dry matter production (B) of FR13A, BR4, and BR5 during postsubmergence period as affected by recovery period after transplanting (Annual Report, Plant Physiology, BRRI, 1981).

stages, the early tillering stage is identified as the stage most vulnerable to flash-flood submergence (Table 10).

Submerged plants produce tillers quickly during the postsubmergence period and attain a tiller number similar to that of nonsubmerged plants (Fig. 7). However, yielding ability depends on the growth of the tillers. For a strong photosensitive variety, the newly grown tillers have less time than that of nonphotosensitive varieties for development and ultimately grain yield is affected (Table 11).

Considering the above points, research work on regrowth of rice plants during the postsubmergence period needs to be emphasized to formulate a technology for reestablishing a crop when stand establishment is totally destroyed because of flash flood.

Crop establishment in receding floodwater

Around 1.8 million ha of rice land are denoted as medium highland phase 2 in the agroecological zones of Bangladesh. In these areas, floodwater rises to a depth of 90 cm and stays for 2 to 3 months. Floodwater recedes to a depth of 30 cm in September or early October.

During recession of floodwater in medium highland phase 2, farmers usually transplant local T. aman varieties for the establishment of a late T. aman crop. The preconditions for the establishment of a late T. aman crop in this ecosystem are strong photoperiod sensitivity and tall seedling height of the variety.

Table 10. Submergence tolerance of rice varieties as affected by recovery period and submergence duration.

	Recovery period (d)	Submergence duration (d)	Submergence tolerance[a]
BR4	4	2	1
		6	3
		10	5
	5	2	3
		6	7
		10	7
BR3	10	2	5
		6	7
		10	7
	5	2	7
		6	9
		10	9

[a]On a scale of 19, where 1 = lowest and 9 = highest.
Source: Annual report, BRRI (1979).

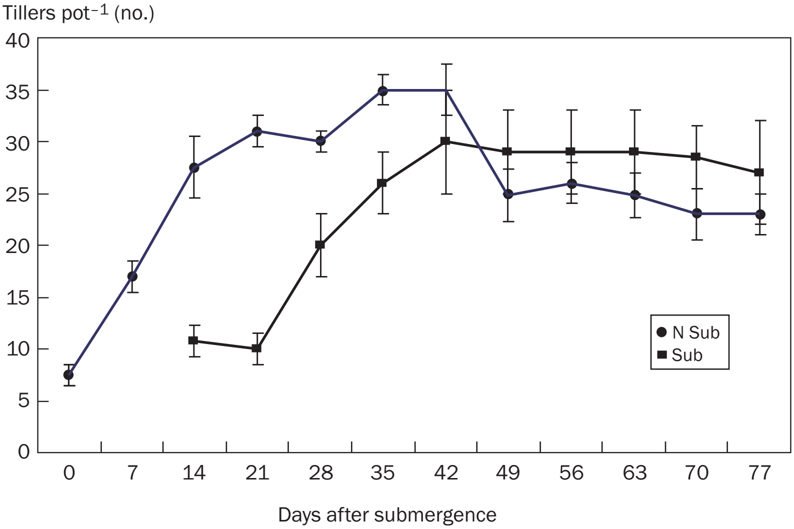

Fig. 7. Tillering pattern of BR32 as affected by submergence. N Sub = no submergence, Sub = submergence.

Table 11. Submergence tolerance and tillering ability of rice varieties as affected by recovery period after transplanting.

Variety	Recovery period (d)							
	Submergence tolerance[a]				Tillers produced (no. line^{-1})			
	15	10	5	0	15	10	5	0
Kumargoir	1	5	9	9	20	11	6	7
Nizersail	3	7	9	9	15	8	6	3
Dulabhog	5	9	7	9	9	4	5	3
IR20	3	9	7	9	10	6	12	3
Dudmona	1	7	7	9	16	11	6	5
BR4	1	3	7	9	11	16	9	5
IR5	3	5	7	9	16	13	7	7
Razasail	1	7	7	9	25	11	8	2
Dharial	3	7	7	9	10	4	5	2
BR3	3	7	9	9	14	11	5	4

[a] On a scale of 19, where 1 = excellent and 9 = very poor.
Source: Annual Report, BRRI (1979).

Recently, the Rice Farming System Division of BRRI established BR22 and BR23 in medium highland phase 2 and a grain yield of 4 t ha^{-1} was achieved (Table 12). If this finding is extrapolated to other medium highland phase 2 environments of the country, the production of high-quality food grain from this part of the flood-prone ecosystem is possible. The strategic plan for the extra rice production of 2.5 million tons has earmarked medium highland phase 2 as a target area where modern high-yielding photosensitive varieties are suggested for establishment in place of local T. aman varieties (Tables 13, 14).

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Table 12. Grain yield (g pot^{-1}) of four T. aman rice varieties as affected by submergence at recovery, tillering, and panicle initiation stages.

Variety	Stage		
	Recovery	Tillering	Panicle initiation
BR11	22.3	0.0	50.9
BRRIdhan 30	31.5	0.0	46.0
BRRIdhan 31	7.7	9.5	36.0
BRRIdhan 32	38.8	18.4	34.6

Source: Annual internal review, Plant Physiology, BRRI (1997).

Table 13. Yield and yield components of three rice varieties as affected by submergence.

Variety	Yield (g pot^{-1})			Panicles pot^{-1}		Filled grains pot^{-1}	
	N Sub	Sub	R. Yield	N Sub	Sub	N Sub	Sub
BR22	75	54	72	24	24	146	116
BR10	61	51	84	25	23	114	117
BRRIdhan 32	46	46	100	22	21	95	100

[a]N Sub = not submerged, Sub = submerged, R. Yield = relative yield.
Source: Annual internal review, Plant Physiology, BRRI (1999).

Table 14. Yield and yield components of photosensitive BRRI and BINA rice varieties at different spacing after boro rice in the medium highland phase 2.

Variety	Treatments		Plant height (kg ha^{-1})	Panicles m^{-2} (no.)	Filled grains panicle^{-1} (no.)	Grain yield (t ha^{-1})
	Spacing	N rate (cm)				
BR22	15 × 15	60	86.3 d	264 bc	79 bcd	4.24 ab
	15 × 10	60	84.5 d	293 abc	74 cde	3.74 bcd
	15 × 5	60	83.3 d	338 a	69 cde	3.25 def
	20 × 15	60	83.2 d	291 abc	85 bc	3.19 efg
BR23	15 × 15	60	87.8 cd	315 ab	54 e	4.50
	15 × 10	60	91.2 cd	288 abc	62 cde	3.75 bcd
	15 × 5	60	87.9 cd	242 c	59 de	3.39 c-f
	20 × 15	60	96.8 bc	239 c	57 de	3.59 cde
Binashail	15 × 15	60	104.6 ab	258 bc	88 ab	3.86 bc
	15 × 10	60	106.9 a	244 bc	109 a	3.00 fg
	15 × 5	60	107.4 a	229 c	103 ab	2.72 g
	20 × 15	60	105.8 ab	260 bc	99 ab	2.86 fg

[a]In a column, values followed by the same letter are not significantly different by Duncan's multiple range test.
Source: Rice farming system, BRRI (1999).

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Nutrient management for rice in the flood-prone ecosystem

G.M. Panaullah, M.S. Rahman, and A.L. Shah

Bangladesh has a complex web of agroecosystems that determine the nature and scope of agricultural enterprises in the country. Almost every year, floods cause colossal damage, but the farmers are usually blessed with relatively rich harvests following a flood. This is largely believed due to enrichment of soils with plant nutrients carried by floodwater. Each year, a major portion of about 2.5 billion tons of nutrient-rich sediments carried by the major river systems is deposited on crop fields. In this paper, we review and analyze available data on nutrient addition to soils from floodwater that could affect soil fertility in the flood-prone ecosystem, and present results of some recent research by BRRI soil scientists on nutrient management for rice in the flood-prone ecosystem. Studies suggested that the sediments contained good amounts of organic matter and substantial amounts of N, P, K, S, Ca, Mg, Fe, Mn, Zn, and B. Nitrogen was found to be the only possible limiting nutrient for rice production in flood-prone areas. Fertilizer recommendations for the different rice-based cropping systems in the flood-prone ecosystem should be based on regular sediment and soil tests to avoid overapplication of fertilizer. Such a fertilization practice will be both cost-effective for farmers and environment-friendly. New N fertilizer management techniques, such as the leaf color chart and the use of urea supergranules and slow-release fertilizers, appeared to be promising for the flood-prone ecosystem.

Bangladesh is actually a floodplain, a delta small in size, but it has diverse physiographic and hydrological features and land and soil types, resulting in a complex web of agroecosystems that determine the nature and scope of agricultural enterprises in the country, and ultimately the lives and livelihoods of her teeming millions. Here, some of the mightiest rivers of the world, the Ganges, the Jamuna (Brahmaputra), the Padma, and the Meghna, and their numerous tributaries flow across the length and breadth of the landscape. The occurrence of annual floods over almost all riverine Bangladesh is the rule rather than the exception.

Floods cause colossal damage in Bangladesh, but it is also true that the farmers are usually blessed with relatively rich harvests following a flood, which is largely believed to be due to enrichment of the soils with plant nutrients carried by the floodwaters. Each year, about 2.5 billion tons of sediment are carried by the major river systems of Bangladesh (Hossain 1992). A major portion of this sediment, carrying a good amount of plant nutrients, is deposited on crop fields. These apparently contrasting features of the floods in Bangladesh may have impelled a journalist to write, "Water completely defines Bangladesh. Every year floods sweep across much of the land. Yet the power of the water to destroy is almost equally matched by its power to create" (C.E. Cobb, Jr., National Geographic, Vol. 183, No. 6, 1993). We interpret this "power to create" as something related, partially at least, to the soil nutrient availability and nutrient management scenario in rice production in the flood-prone ecosystem of Bangladesh. In this paper, we attempt to present a brief review and analysis of available data on nutrient addition to soils from floodwaters that could have a bearing on soil fertility in the flood-prone ecosystem, and results of some recent research by BRRI soil scientists on nutrient management for rice in the flood-prone ecosystem.

Floodwater sediment: potential plant nutrient sources

Bangladesh experienced its most devastating prolonged flood in 1998. A team of soil scientists assessed the effects of this flood on the fertility of the country's soils. Fresh sediment and old topsoil samples from 110 sites representing the different river systems of the country were collected and analyzed for physico-chemical and chemical properties influencing soil fertility. Almost everywhere, the sediment was found to be chemically compatible with the normally expected soil fertility indices, and to contain appreciable quantities of available plant nutrients that had the potential to improve the fertility status of the soils (Idris 1999). The pH of the sediment ranged from 5.0 to 8.0, a safe range for plant nutrient availability. The sediment contained good amounts of organic matter (OM) important for the low-OM soils of Bangladesh. Plant nutrients such as N, P, K, S, Ca, Mg, Fe, Mn, Zn, and B carried by the sediment were also quite substantial, which would improve the fertility of the soils flooded. In fact, luxuriant growth of black gram grown on the fresh sediment at Shibganj was observed (Idris 1999). Moreover, bumper harvests of rabi and T. aman crops in 1998-99 following the devastating flood of July-August 1998 provide circumstantial evidence of soil fertility improvement caused by sediment deposition. Table 1 shows some examples of sediment-carried plant nutrients at various flood-prone locations. A study on sedimentation at the BRRI Regional Station in Habiganj, situated in a traditional flood-prone zone (deepwater) in northeastern Bangladesh, was carried out from 1992 to 1996. The flooding depth at the BRRI Regional Station-Habiganj experimental farm is generally 1–4 m. From 1992 to 1996, except in 1994, the total yearly sediment deposition on the farm was around 2,000 kg ha^{-1}, which added 22, 22, 46, 4, and 0.4 kg ha^{-1} of N, P, K, S, and Zn to the soil (Table 2) (Shah et al 2000). The sediment also contained a high amount of organic matter, around 5%. A similar study was conducted by the BRRI Soil Science Division in 1999 at the BRRI Regional Station in Bhanga, situated in the flood-prone ecosystem in central Bangladesh. In that year, on parts of the farm flooded to a depth of 1–2 m, the total sediment

Table 1. Chemical properties of sediments deposited at various locations of Bangladesh during the flood of 1998.

Position	Sediments/soils	pH	OM[a] (%)	TN (%)	Ca	Mg	K	P	S	Zn	Fe	Mn	B
					(meq 100 g^{-1})			(µg g^{-1})					
Ganges River system (*Shibganj thana*)													
River bank (RB)	Sediments	7.8	0.40	0.05	21.8	1.08	0.12	3.2	8.9	0.29	7.4	4.0	0.27
	Old topsoils	7.9	1.31	0.08	23.5	1.19	0.19	4.6	12.3	0.32	8.9	5.0	0.33
Away from RB	Sediments	7.9	0.76	0.06	23.3	1.33	0.16	3.4	10.8	0.21	6.4	3.9	0.21
	Old topsoils	8.0	0.99	0.08	24.2	1.27	0.22	9.4	7.5	0.13	8.9	4.5	0.26
Tista, Dharala, and Atrai River system (*Chilmari thana*)													
River bank	Sediments	7.3	0.55	0.04	4.3	1.66	0.07	4.4	18.4	0.42	11.5	7.2	0.15
	Old topsoils	7.3	0.54	0.12	2.7	1.43	0.06	3.7	13.4	0.33	19.6	2.8	0.17
Away from RB	Sediments	7.4	0.92	0.05	5.4	2.09	0.11	5.8	35.2	0.44	19.8	9.8	0.24
	Old topsoils	7.6	1.63	0.07	6.5	3.04	0.20	3.6	62.3	0.53	35.6	12.8	0.17
Jamuna River system (*Sirajganj thana*)													
River bank	Sediments	7.0	0.54	0.03	5.4	1.85	0.12	6.1	48.7	0.39	17.8	6.9	0.21
	Old topsoils	7.1	0.95	0.05	5.6	2.05	0.18	4.9	25.6	0.45	41.8	13.6	0.21
Away from RB	Sediments	7.3	0.78	0.05	6.7	2.43	0.22	6.0	39.8	0.47	35.7	19.6	0.24
	Old topsoils	6.3	0.88	0.05	4.4	1.70	0.18	7.4	23.5	0.45	81.9	37.6	0.25
Kushiara and Gomoti River system (*Beanibazar thana*)													
River bank	Sediments	5.2	1.45	0.08	5.1	2.97	0.11	5.3	53.2	0.64	114.7	46.0	0.10
	Old topsoils	6.0	1.40	0.07	7.0	4.10	0.09	6.1	24.8	0.78	47.4	49.0	0.14
Away from RB	Sediments	5.8	1.73	0.09	6.3	3.37	0.14	1.4	79.1	0.79	118.2	68.7	0.24
	Old topsoils	6.7	0.82	0.04	6.5	3.85	0.08	5.9	15.1	0.72	43.0	20.8	0.40

[a] OM = organic matter, TN = total nitrogen.

Source: Idris (1999).

Table 2. Sediment and nutrient deposition at BRRI Regional Station-Habiganj, 1992-96.

Year	Sediment deposition ($t\ ha^{-1}$)	Nutrient deposition ($kg\ ha^{-1}$) N	P	K	S	Zn
1992	2.11	23.9	25.3	50.7	7.0	0.5
1993	2.04	22.9	22.5	47.0	3.9	0.4
1994	0.52	6.0	6.2	12.4	2.0	0.1
1995	1.97	22.5	21.1	41.4	8.5	0.4
1996	2.25	25.4	24.5	45.0	11.3	0.4

Source: Shah et al (2000).

Table 3. Sediment and nutrient deposition at BRRI, Bhanga, 1999.

Sediment collection site	Sediment deposition ($t\ ha^{-1}$)	Total nutrient added ($kg\ ha^{-1}$) N	P	K	S	Ca	Mg	Zn
Shallow (1 m depth)	1.2	3.3	3.0	33.0	6.0	38.4	24.5	0.1
Deep (>2 m depth)	1.5	3.0	3.5	35.0	7.0	48.8	29.8	1.0

Table 4. Chemical properties and nutrient status of soils of different BRRI farms and grain yield of BR3, BRRI greenhouse, Gazipur, 1999.

Soils	pH	Organic C (%)	Total N %	P (ppm)	K (meq 100 g^{-1})	Grain yield (g pot^{-1})
Bhanga	7.5	1.8	0.3	34	0.45	37.7
Comilla	6.4	1.8	0.1	35	0.2	32.3
Gazipur	6.7	1.1	0.1	11	0.2	23.3
Habiganj	4.5	2.0	0.2	4	0.4	33.4

deposition was about 1,000 kg ha^{-1}, and, on parts flooded to a greater depth (>2 m), it was about 1,500 kg ha^{-1}. The organic matter content of the sediment was high, 3–4%, and the sediment added appreciable quantities of plant nutrients to the soil (Table 3).

Soil tests run on samples from four BRRI experimental farms, Gazipur (flood-free), Comilla (flood-free), Habiganj (flood-prone), and Bhanga (flood-prone), indicated relatively high soil fertility on the farms under the flood-prone ecosystem (Table 4). In a simple pot experiment with soils from the four experimental farms conducted at a single place (Gazipur) to eliminate climatic variation, rice on the Habiganj and Bhanga soils significantly outyielded that on the Gazipur and Comilla soils (Table 4).

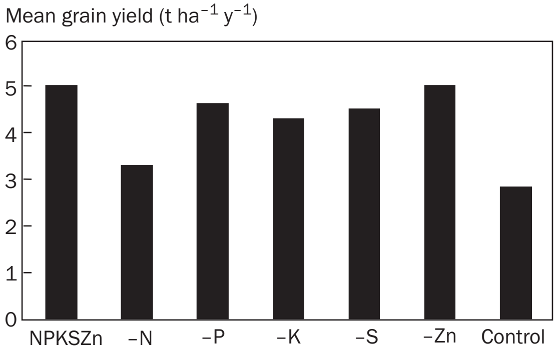

Fig. 1. Average grain yield of modern variety rice (BR3) under balanced and incomplete fertilization practices, BBRI, Gazipur, 1985-99.

The Bhanga and Habiganj soils are replenished with nutrients annually by sediments caused by flooding.

Nutrient management

Proper identification and management of nutrient deficiency (or toxicity, if any) in the soil are a prerequisite for boosting rice production and sustaining high yield under any environment, especially in less favorable ecosystems. To identify an appropriate nutrient management option for growing rice in the flood-prone ecosystem, a long-term experiment was conducted by the BRRI Soil Science Division at the BRRI Regional Station-Habiganj. A single rice crop (boro, BR3) was grown in each year. The experiment was a "missing element" trial in which a complete NPKSZn treatment and "nutrient missing" treatments, such as complete minus N, P, K, etc., were compared. A similar trial was also simultaneously conducted at BRRI headquarters in Gazipur (flood-free), where a double rice-cropping (boro-T. aman) pattern was followed. In these long-term trials, N, P, and K deficiencies severely limited yield at Gazipur, whereas at Habiganj only N was a significant yield-limiting factor (Figs. 1 and 2). Without any fertilizer, the boro rice yield was 5 t ha^{-1} at Habiganj but only around 3 t ha^{-1} at Gazipur. The maximum yield with the complete treatment at Habiganj was almost 7 t ha^{-1}, about 2 t ha^{-1} more than that at Gazipur. Thus, the achievable rice yield in the flood-prone ecosystem has always been higher with similar nutrient doses and management under irrigated culture.

Nitrogen management

Variety BRRIdhan 29, with a higher yield potential than BR3, is replacing the latter variety in the single-cropped flood-prone ecosystem. Since the soils in this ecosystem contain relatively high amounts of organic matter and total N, we studied N management for the variety. Two trials were conducted in boro 2000, one at the

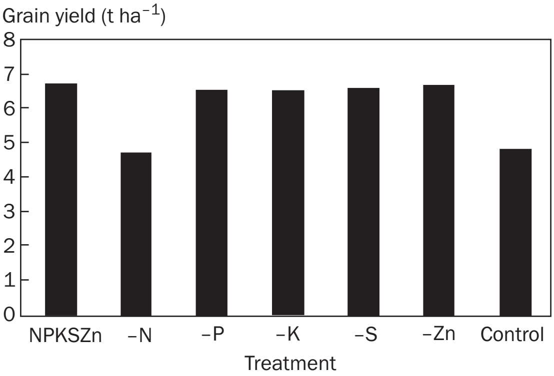

Fig. 2. Average grain yield of modern variety rice (BR3) under balanced and incomplete fertilization practices, BRRI, Habiganj, 1988-97.

BRRI Regional Station-Bhanga and the other at the BRRI Regional Station-Habiganj. The soils at Bhanga and Habiganj contained 0.25% and 0.23% total N, respectively. The Habiganj soil was acidic (pH 4.44) and the Bhanga soil was alkaline (pH 7.40). Six N doses (0, 40, 80, 120, 160, and 200 kg N ha^{-1}) were tested. Blanket doses of 15 kg P ha^{-1}, 40 kg K ha^{-1}, 10 kg S ha^{-1}, and 2 kg Zn ha^{-1} were applied at each location. The major findings were

- The grain yields in the 0-N plots at Bhanga and Habiganj were 5.09 and 5.53 t ha^{-1}, respectively. The application of N fertilizer increased grain yield at both locations. The highest grain yield at Bhanga was 8.05 t ha^{-1} and at Habiganj it was 7.25 t ha^{-1} (Fig. 3).
- The yield response at Bhanga could be explained by the equation

$$Y = 4.99 + 0.03467N - 0.0001N^2$$

- The calculated rate of N that maximized yield at Bhanga was 173 kg ha^{-1} and the economic optimum rate was 165 kg ha^{-1}.
- The yield response at Habiganj was of the form

$$Y = 5.85 + 0.02429N - 0.00012N^2$$

- The calculated N dose for maximum yield at Habiganj was 101 kg ha^{-1} and the economic optimum rate of N was 94 kg ha^{-1}.
- Although the soils at both locations had a relatively high total N content, there was a high response to applied N, which seemed to be unusual. Probably, the mineralization of the soil organic matter N was being slowed down by some unidentified nutrient deficiency/toxicity. In-depth studies on N mineralization in these soils should be undertaken.

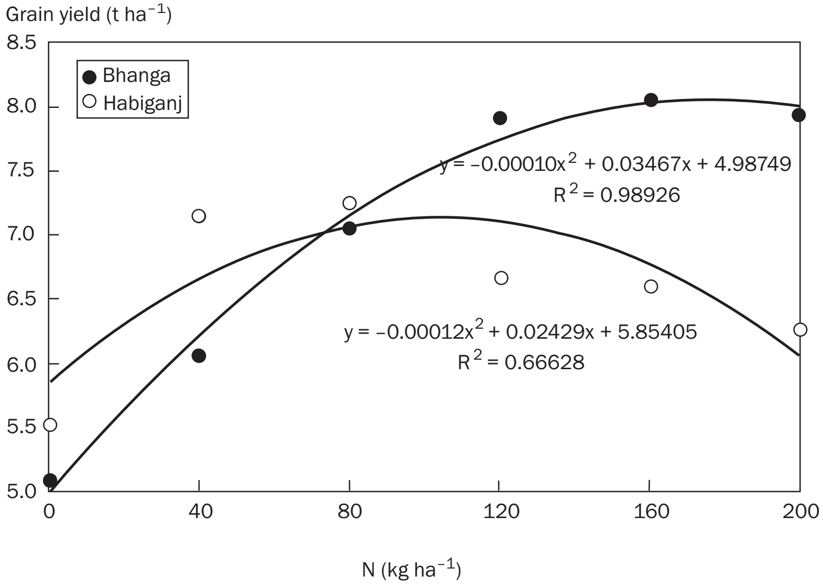

Fig. 3. Response of rice to applied N at BRRI Regional Station, Bhanga and Habiganj, boro 2000.

We also tested a recently developed N management tool—the leaf color chart (LCC). The LCC is a relatively simple tool for indirectly measuring the N status of the leaves. The LCC has different shades of green imprinted on it. By comparing the greenness of the leaves with the help of the LCC *in situ*, farmers may be able to decide whether and when to apply N.

A field experiment was conducted at the BRRI Regional Station-Bhanga in boro 2000 with BRRIdhan 29 as the test variety. Two LCC threshold levels of 4 and 5 (differing shades of green) were evaluated along with the BRRI-recommended split-N dose using 140 kg N ha^{-1} and N control. Weekly LCC scores were taken starting from 25 to 30 days after transplanting (DAT) until the ripening stage. Nitrogen topdressing was done with 30 kg N ha^{-1} when the observed LCC value dropped below the set threshold values. A small basal dose of 30 kg N ha^{-1} was applied to the LCC-N plots. All the treatments received recommended rates of P, K, S, and Zn. The following observations were made:

- The LCC-based N treatment recorded a significantly higher yield over the control, but showed no significant difference with the recommended split-N treatment (Table 5).
- The LCC-4 and LCC-5 N treatment consumed only 60 and 90 kg N ha^{-1} to produce grain yields of 8.02 and 8.13 t ha^{-1}, respectively.

Table 5. Grain and straw yields and N-use efficiency of BRRIdhan29 under different N management practices. BRRI, Bhanga, boro 2000.

N treatment	N applied (kg ha^{-1})	No. of N splits	Grain yield (t ha^{-1})	N uptake (kg ha^{-1})	AEN[c]	PFP-N[d]	PEN[e]	REN[f]
N-control	0		5.97	71.0				
BRRI recommendation[a]	140	3	8.35	107.0	17	60	66	0.26
LCC-4 N[b]	60	2	8.02	100.7	34	134	69	0.49
LCC-5 N[b]	90	3	8.13	88.7	24	90	122	0.20
LSD (0.05)	–	–	0.53	21.5	–	–	–	–

[a] 1/3 basal + 1/3 at active tillering + 1/3 at panicle initiation. [b] LCC-based topdressing (30 kg N ha^{1}) without basal N. [c] AEN = additional grain yield over control per kg N applied. [d] PFP^{N}= total grain yield per kg N applied. [e] PEN = physiological efficiency of N = additional grain yield over control per kg N absorbed by the plant from applied N. [f] REN = recovery efficiency of N = increase in total N uptake over control from the total N applied.

- The LCC-based N management appeared to be more efficient than the conventional N management practice.
- The agronomic efficiency of N (AEN) values were appreciably high (34) for the LCC-4 N treatments compared with those for the LCC-5 N (24) and BRRI recommendation (17) (Table 5).
- The partial factor productivity (PFP) for applied N followed the same trend as the AEN. Higher PFP-N values of 134 were recorded for the LCC-4 N treatments compared with 90 and 60 for LCC-5 and conventional N splits, respectively.
- The LCC-4-based N management gave the highest N recovery (49%).

In the relatively shallow flood-prone ecosystem, T. aman rice in addition to boro may be grown. Because of the unpredictable floods, farmers often fail to apply the split-N doses according to the proper schedule and the crop is affected by N deficiency at the critical later stages of growth. In such situations, a one-time basal application of N fertilizer in the form of urea supergranules (USG) or some slow-N-release fertilizer instead of the recommended split application of prilled urea (PU) may be a better choice. Table 6 shows the advantage of USG over PU for T. aman rice in a shallow flooding (80 cm) situation in Barisal. The comparatively higher efficiency of USG relative to PU in boro rice has also been demonstrated in different flood-prone areas of the country (Table 7).

Phosphorus management

The soils of the BRRI Regional Stations at Bhanga and Habiganj are fertile. Soil tests for available P gave a value of 20 ppm for Bhanga, but a very low value of <4 ppm for Habiganj, although both soils yield 7 to 8 t ha^{-1} (boro, BRRIdhan29). A study was conducted to determine appropriate P fertilizer doses for the two situations. Six P doses—0, 6, 12, 18, 24, and 30 kg P ha^{-1}—were tested with BRRIdhan 29. Blanket doses of N, K, S, and Zn were applied at 90, 40, 10, and 2 kg ha^{-1}, respectively.

Table 6. Effect of N sources and application schedules on the performance of modern and local rice varieties, BRRI Regional Station, Barisal, T. aman, 1994.

N source and method of application[a]	Grain yield (t ha^{-1})		Straw yield (t ha^{-1})	
	BR23	Sadamota	BR23	Sadamota
0 N	3.56 b	3.22 a	3.24 a	4.10 b
Prilled urea (PU): all basal	3.42 b	3.18 a	3.56 a	4.61 b
PU: 3 splits	3.72 b	3.28 a	3.37 a	4.32 b
PU: after final recession of tidal waters	3.67 b	3.29 a	3.94 a	4.64 b
Urea supergranules: point placement	4.44 a	3.62 a	3.75 a	5.94 a
CV (%)	7.5	–	12.1	–
LSD: variety means	0.2 (5%)	0.27 (1%)	0.5 (1%)	–

[a] N rate: 60 kg ha^{-1} for modern varieties, 30 kg ha^{-1} for local varieties.
Source: BRRI (1994).

Table 7. Yield advantage of urea supergranules (USG) over prilled urea (PU) in flood-prone areas, boro 1999.

Location[a]	N rate (kg ha^{1})		Grain yield (t ha^{-1})		Grain yield (t ha^{-1})	N savings (kg ha^{-1})
	USG	PU	USG	PU		
Manikgang (3)	80	140	7.0	5.9	1.1	60
Munshigang (1)	80	100	8.5	6.5	2.0	20
Chandpur (4)	72	102	9.6	7.9	1.7	30
Tangail (24)	72	112	7.6	6.6	1.0	40
Jamalpur (28)	72	112	8.2	7.1	1.1	40

[a] Numbers in parentheses indicate number of farmers' fields per site.
Source: IFDC (2000).

Figure 4 presents the grain yields of rice. Rice at Bhanga yielded slightly higher than at Habiganj, but the response of rice to P fertilizer was not significant. The grain yields of rice in the P-control plots at Bhanga and Habiganj were 7.89 and 6.83 t ha^{-1}, respectively. At both locations, an inconsistent response to P was observed. The lack of response to P at Bhanga could be explained since the soil had quite a high level of available P, but the results from Habiganj were unexpected given the very low level of available P in the soil. Probably, the conventional analytical method was not appropriate for assessing available P in this strongly acidic soil with a high organic matter content.

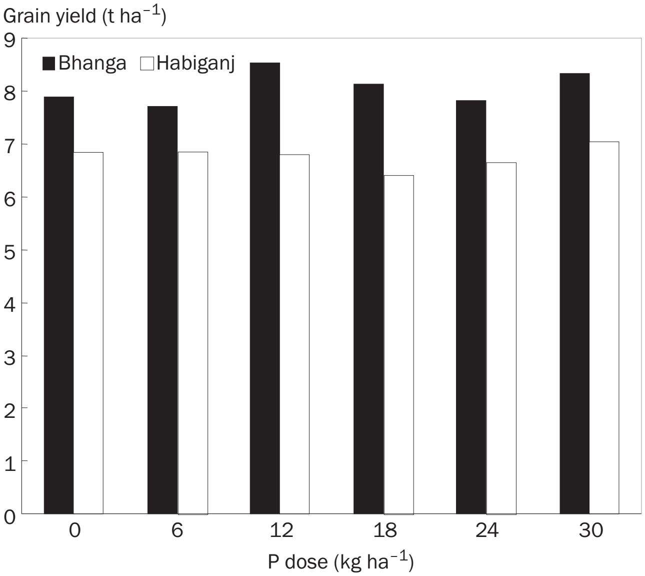

Fig. 4. Response of rice to applied P at BRRI Regional Station, Bhanga and Habiganj, boro 2000.

Conclusions

Sediment carried by floodwater is rich in plant nutrients, which can improve soil fertility in the flood-prone ecosystem. Annual replenishment of the soils with plant nutrients in flooded areas should be helpful in maintaining a positive nutrient balance in the soils and ensuring the sustainability of the cropping systems.

Fertilizer recommendations for the different rice-based cropping systems in the flood-prone ecosystem should be based on regular sediment and soil tests to avoid overapplication of fertilizer. Such a fertilization practice will not only be cost-effective for farmers but will also be environment-friendly.

New N fertilizer management techniques, such as the LCC and the use of USG and slow-release fertilizers, etc., appear promising for the flood-prone ecosystem. Research and technology development-dissemination in this respect are in order.

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Managing weeds in flood-prone rice systems

G. Jashim, U. Ahmed, and M.A. Jabbar

This paper reviews the weed control practices adopted by farmers and improved weed management for flood-prone rice. In flood-prone areas, four types of rice are grown: aus-aman mixed, single broadcast aman and deepwater aman, and boro. The first three are sown in dry soil. In dry seeding, weed competition occurs mostly during stand establishment and the early to mid-vegetative stages of the rice crop. In deepwater rice (DWR), a weed shift occurs when flooding starts. Terrestrial weeds disappear and aquatic weeds grow and compete with DWR. Floating weeds such as *Eichhornia crassipes* and *Pistia stratiotes* may intrude into the rice field along with floodwater and may cause serious problems. Wild rice species having tolerance for flooding and elongation ability are a serious threat to DWR. Farmers in these areas use tillage, raking, manual and mechanical weeding, and fencing devices to prevent the entry of floating weeds into rice fields. In dry-sown rice, hand weeding and raking are popular practices for weed control. Herbicides such as butachlor, thiobencarb, and oxadiazon (Ronstar 25EC) are also effective for controlling weeds in dry-seeded rice. To control floating weeds, fencing around the field is still a very popular method as no other cost-effective weed control method is available to control them. In boro rice, farmers' weed control is gradually shifting from traditional practices to modern ones. Herbicides such as oxadiazon, cinosulfuron, and butachlor are effective in controlling weeds in boro rice and are gaining popularity day by day. The development of integrated weed control technology is essential for effective and economical weed control of rice in flood-prone lands.

The floodplains of Bangladesh may remain under water for 7–9 months (March-November) because of the overflow of mighty rivers such as the Padma, Brahmaputra, Meghna, and Surma-Kushiyara, which affects farming systems and the livelihood of millions of farmers. The depth of flooding varies from 50 cm to more than 3.0 m. There are many natural depressions in the floodplain, which are called *baors*, *haors*, *beels*, or *jheels*. Perennial water bodies are observed at the center or in the deepest areas of those depressed lands. A flood-prone area usually remains dry from November to May, which varies depending on the time of the onrush of floodwater. The soils of all flood-prone areas may be slightly alkaline or slightly acidic, with different soil mineral contents. There are also differences in biophysical environments among the floodplains. The farmers in flood-prone areas grow different crops, with rice as the principal one. Four types of rice are grown: boro, aus, mixed aus-aman, and single B. aman/deepwater rice. Boro is transplanted during December to February depending on the recession of floodwater, availability of irrigation, and soil characteristics. Aus rice is sown in March-April and mixed aus-aman and single B. aman or deepwater rice (DWR) from March to mid-May. The dry-sown aus, mixed aus-aman, and DWR encounter serious weed infestations and repeated weedings are needed. In most cases, proper weed control is not possible because of severe weed problems. The boro crop is infested with semiaquatic and aquatic weeds. In the recent past, farmers' only option for weed control was hand weeding when weeding labor was abundant at the farm level. But, with the increasing demand for labor in nonagricultural sectors, the scarcity of labor is rising. So, farmers are gradually shifting to weed control through modern practices that do not involve hand weeding. Therefore, weed management in the flood-prone areas has become a crucial and dynamic factor in rice production.

The flood-prone environment and the rice crop

A considerable area of Bangladesh is submerged annually from May to December or part of this period, with water depth varying from just inundation to more than 4 m under normal flooded conditions. The floodplain areas of the Ganges, Brahmaputra, Tista, Surma-Kushiyara, and other rivers occupy about 70% of the country. Contrary to the flatness of the floodplain, there are some saucer-shaped areas called *haor* and *beel*, which are chronically flood-prone. The Ganges, Brahmaputra, Meghna, Surma-Kushiyara, and their tributaries change the course of their channels, leaving behind vast basins and old channels. The Brahmaputra changed into its present Jamuna channel about 180 years ago, almost abandoning its former floodplain in Mymensingh and Dhaka. Almost all the big rivers have a history of changing course and they have left behind a vast area prone to flooding. So, natural depressions locally known as *baors, haors,* or *beels* are endowed with a flood-prone environment because of the changing course of the rivers. In addition, large areas flooded with large amounts of water from mighty river systems are also a part of the flood-prone environment. Since flooding occurs from May to November, it influences the whole cropping and farming system of the area. During flooding time, only the rice crop is grown in the basin under different flooding depths. Photoperiod-sensitive varieties with longer duration are grown at higher depth and with short duration at a shallow depth of water. After floodwater recedes in November and after harvest of the B. aman crop, the fields are prepared for the rabi crop or other rice cultivation. In some areas, after harvesting the rabi crop, these fields are used for a B. aman crop. After growing a short-duration rabi crop (pulse and mustard), some farmers grow a single aus crop or aus + B. aman as a mixed crop. In deep places of haors and beels, after the recession of floodwater, only boro rice is grown. About three decades ago, DWR was the principal crop in the flood-prone areas, covering almost 2 million ha. Now, the area has decreased to about 0.8 million ha (Nasiruddin 1993). These areas may decline further with the cultivation of modern boro varieties. With this changing situation, farmers' weed control practices are also changing.

Weed infestation in the flood-prone environment

In the flood-prone areas, both aquatic and terrestrial environments are present. After floodwater recedes, the land becomes terrestrial except in the central zones of deep haors. When the boro crop is grown with irrigation, it thrives in a semiaquatic environment. Since weed infestation depends on the environment and crop production practices, the weed species and their populations are also diverse in nature. In dryland conditions, sole aus, aus + B. aman mixed, and sole DWR are sown. Since the soil remains submerged for 6–9 months, annual weeds are dominant in that condition. Annual weed seeds, which remain submerged during flooding, mostly remain viable and germinate quickly with favorable conditions after the recession of floodwater. These weeds compete strongly with crops grown under dry soil conditions. Farmers need repeated weeding and raking to save the crop. As sole aus, some modern and short-duration varieties are grown that need more weeding than local varieties (Hoque et al 1976). The aus + B. aman mixed crop and sole B. aman crop are infested severely with upland weeds at the early growth stage in dry soil. Establishment of these crops depends mainly on weed control. These crops remain in dry-bed conditions for about 2 months. After germination of the seeds in dry soil, the principal impediment faced by the crop is weeds. If weeds smother the crop, it has little chance to reach optimum yield. So, farmers have to use their efforts and resources to keep the crop free from weeds. After the onrush of floodwater, annual and perennial aquatic weeds appear and compete with rice. Moreover, water hyacinth and water lily *(Pistia stratiotes*) begin to enter into the rice field from deep haors or rivers. If these are not controlled, they reduce the plant stand and ultimately damage the crop. To check the invasion of aquatic (floating) weeds, farmers grow hedge plants or make a barrier with bamboo poles to protect the crop during flooding. If the crop establishment is good and optimum plant growth with an optimum stand is achieved by weed control during the dry period, the rice plants become competitive with the growth of aquatic weeds. If the crop has good canopy development, it reduces the sunlight that reaches the soil surface and thus reduces the germination and growth of aquatic weeds. So, weed control is crucial for rice sown prior to flooding in flood-prone areas. Since grain yield expectation is low from the rice crop sown in dry soil, farmers' resource allocation for weeding is also low. Thus, dry-sown rice remains weedy and a considerable yield loss occurs. So, under their agroecological and socioeconomic conditions, farmers need a low-cost weed control technology for dry-sown rice. On the other hand, the boro crop is grown under favorable weather conditions with a high expectation of grain yield. Farmers always take much care and allocate more resources for weed control in boro. Moreover, several weed control technologies are available for boro cultivation, which is grown under fully irrigated conditions. Since weeds are a serious problem of all rice grown in flood-prone environments, weed control is a priority task of farmers to save the crop and obtain optimum yield.

Table 1. Yield loss caused by weed competition in rice.

Cultivar	Crop yield (kg ha^{-1})		Yield loss (%)
	Weed free	Farmers' method	
Aus rice			
Highland			
Chandina	3,300	2,050	37.9
Bogi	3,600	2,700	25.0
Ikorchalboila	3,000	2,100	30.0
Agali	3,900	3,450	11.5
Mean			26.1
Medium land			
Bogi	3,500	2,675	23.6
Agali	3,375	2,886	14.5
Mean			19.0
Lowland			
Agali	3,120	2,650	15.1
Boro rice			
Lahaja	2,860	2,594	9.3
Madhob sail	2,650	2,438	8.0
Hajeshail	3,120	2,761	11.5
Pajam	3,760	3,440	8.9
Biplab	4,677	4,127	11.8
Mean			9.9

Weed control in different rice crops grown in flood-prone environments

Since rice is grown in terrestrial, aquatic, and semiaquatic environments, weed control methods and costs are also different. Traditional weed control practices have been going on for centuries and new effective options are also becoming popular for weed control.

Weed control in aus rice. After thorough land preparation, crop seeds are broadcast (70–90 kg ha^{-1}) over the fields. The weeds and crop seeds germinate and grow simultaneously. So, weeds are a serious problem and need early attention to control them. If weeds are not controlled properly, a significant yield loss can occur (BRRI 1981, Mian and Karim 1970). A study was made to determine crop loss caused by weed competition in aus rice in a village prone to flooding (Mamun 1988). The yield loss was determined in farmers' fields where farmers also did weeding. In unweeded conditions, severe yield loss was observed and this loss varied with the land topography and cultivar (Table 1). In highland, the highest yield loss (38%) occurred with modern cultivar Chandina and the lowest with a traditional cultivar. The medium land, where a local variety was grown, also had different amounts of yield loss. In medium lowland and lowlands, yield losses averaged 19% and 20%, respectively.

Crop loss from uncontrolled weed growth was reported to be about 67% (Mamun 1988). Numerous grass, sedge, and broadleaf species germinate along with rice in the

Table 2. Important weeds in the aus crop.

Crop	Local name	Scientific name	Life cycle	Relative abundance (%)
Aus rice	Pukkera	*Fimbristylis dichotoma*	Perennial	55
	Panighash	*Lindernia anagalis*	Annual	44
	Barapukkera	*Fimbristylis miliaceae*	Annual	30
	Kalagachi	*Murdannia nudiflora*	Annual	34
	Sagaldari	*Cyperus iria*	Annual	16
	Bilailengur	*Digitaria sanguinalis*	Annual	18
	Alleghash	*Echinochloa colona*	Anuual	13
	Satidhaa	*Cyperus compressus*	Annual	14
	Doorba	*Cynodon dactylon*	Perennial	9

aus rice field and cause severe infestation. Aus rice is generally grown in areas with shallow or medium flooding depth. Before sowing of aus, a short-duration rabi crop may be grown in areas where floodwater recedes early. All these conditions influence the weed community of the shallow-flooded and deep-flooded zones. In a survey at Jawar, a village in the Meghna estuarine floodplain, 44 weed species were found in an aus rice field (Mamun 1988). Among these, nine belonged to Gramineae, ten to Cyperaceae, and others to the broadleaf group. *Fimbristylis dichotoma* was the highest in relative abundance, followed by *Lindernia anagalis,* which was found to occur in the highest number of fields and sampling locations.

In general, grass and sedge constitute the major part of the weed vegetation in aus rice (Table 2). Since aus rice suffers from serious weed infestation, control is tedious, time-consuming, and costly. Weeds are generally controlled by raking and hand weeding (Ahmed and Islam 1998). The rake is a traditional bullock-drawn implement made of a wooden body, beam, and handle with several bamboo tines fitted throughout the lower side of the body at approximately equal distance. The implement is used to control germinating weeds, thin the crop, and even break the soil crust after sowing. Bamboo tines of the rake do not penetrate the soil below 2–3 cm. Raking is generally done in one direction but some farmers practice cross-raking. In aus, raking is always followed by laddering. Laddering is done to crush soil clods formed by raking. In local varieties, 2–3 rakings and ladderings are practiced, but, in modern rice, one is generally done. This operation is carried out even 1 month after sowing. The time of raking and laddering is usually related to rain. It usually follows 4–7 days after rain when the weeds start to germinate. This method controls the first emerging weed flush and reduces the labor of subsequent hand weeding. Through this practice, a large area may be weeded within a short period of time and all kinds of weeds can be uprooted at the germinating stage. It also facilitates exposure of weed seeds to heavy rainfall and intense sunshine. Raking is essentially done in mixed aus-B. aman and sole B. aman rice to control weeds.

Hand weeding in the aus rice field is done with simple tools called *nirani* and *sen-pachon*. It is also done with bare hands. Three hand weedings are required for

Table 3. Herbicide use in different rice culture.

Herbicide	Doses (ai ha^{-1})
Upland (aus)	
Ronstar 25EC	1.0 L
Thiobencarb	1.5 L
Butachlor	1.5 L
Lowland	
Ronstar 25EC	2 L
Ronstar 12L	23 L
Setoff 20WG (cinosulfuron)	50 g
Gotler 5G (butachlor)	1.5 kg
2, 4-D	600 mL

modern aus rice. Local aus rice requires fewer weedings (1–2) for its faster seedling growth and quicker canopy development than modern varieties, which may require 3 or more. Forty days of weed-free period is considered essential for aus rice to obtain optimum yield. Preemergence herbicides—butachlor, thiobencarb, and oxadiazon—are effective for controlling weeds in aus rice (Table 3).

Weed control in aus-B. aman mixed cropping. A considerable area of shallow- to medium-flooded land is sown with aus and B. aman as a mixed crop. The aus crop is of short duration and, being insensitive to photoperiod, flowers 75–85 days after seeding according to the genetic character of the variety and matures before rainy-season flooding. The aman crop, which is sensitive to photoperiod, continues to grow and flowers in October and November. The mixed aus–B. aman rice is grown after the water recedes. Aus and B. aman seeds in different proportions are seeded in dry soil. The weeds and crop seeds germinate together; therefore, weed competition is serious at the early growth stage of the crop. Raking and laddering operations are generally done at the early growth stage to control germinating weeds. When the crop plants become tall enough, hand weeding is done along with *nirani* and *sen-pachon*. Generally, 2–3 hand weedings are required for the crop, but, in some cases, even 4 hand weedings are done. In a study in mixed aus–B. aman rice, it was observed that grasses predominate in the dry period and sedges begin to grow abundantly when the soil reaches moist conditions (Mamun 1988). The weed species were *Cynodon dactylon, Cyperus rotundus, Alternanthera sessilis, Echinochloa colona,* and *E. crus-galli*. After the onset of monsoon, weed species such as *Cyperus difformis, Jussiaea repens, Paspalum scrobiculatum, Commelina diffusa, Cynotis axillaries,* and *Cyperus iria* became dominant under moist conditions. After the intrusion of floodwater, weeds such as *Leersia hexandra, Aponogeton crispum, Alisma plantago, Pistia stratiotes, Ipomoea aquatica, Azolla pinnata, Lemna trisulca, Eichhornia crassipes,* and *Nymphaea* sp. became dominant on standing water. Since weed infestation is severe at the early growth stage, that is, before the intrusion of floodwater, much effort is needed at that time to remove the weeds in order to avoid high yield loss. In his study, Mamun (1988) observed that Tk 3,280 and Tk 5,800 (US$1 = Tk 55), respectively, were needed to control weeds (Tables 4 and 5) in mixed aus-aman

Table 4. Cost of weeding at Dakhshin Chamuria.

Crop	Weeding method and schedule	Time of weeding[a] (DAS)	Labor requirement		Cost (Tk ha^{-1})
			Bullock pair	Person-days	
Aus + B. aman rice	1st raking	10–15	1	1	80
	1st laddering	10–15	2	2	160
	2nd raking	20–25	1	1	80
	2nd laddering	20–25	2	2	160
	1st hand weeding	35–40		45	1,800
	2nd hand weeding	60–65		25	1,000
Total cost					3,280

[a]DAS = days after sowing.

Table 5. Cost of weeding in rice at Jawar village.

Crop	Weeding method and schedule	Time of weeding[a]	Labor requirement		Cost (Tk ha^{-1})
			Bullock pair	Manday	
Aus rice (modern)	1st raking	10–15 DAS	2	–	160
	1st laddering	10–15 DAS	2	–	160
	2nd raking	25–30 DAS	2	–	160
	2nd laddering	25–30 DAS	2	–	160
	1st niri	35–40 DAS	–	50	2,000
	2nd niri	50–60 DAS	–	30	1,200
Total	3,840				
Aus rice (local)	1st raking	10–15 DAS	2		160
	1st laddering	10–15 DAS	2		160
	1st niri	35–40 DAS	–	50	2,000
	2nd niri	50–60 DAS	–	30	1,200
Total					3,520
Aus + B. aman mixed	1st niri	15–20 DAS	–	60	2,400
	2nd niri	35–40 DAS	–	40	1,600
	3rd niri	55–60 DAS	–	30	1,200
	4th niri	60–70 DAS	–	15	600
Total					5,800
Boro (modern)	1st hand weeding	20–25 DAT	–	40	1,600
	2nd hand weeding	40–45 DAT		30	1,200
	3rd hand weeding	50–55 DAT	–	20	800
Total					3,600
Boro (local)	1st hand weeding	20–25 DAT	–	40	1,600
	2nd hand weeding	45–50 DAT		20	800
Total					2,400

[a]DAS = days after sowing, DAT = days after transplanting.
Source: Mamun (1988).

rice in flood-prone areas. Hasanuzzaman (1975) reported that mixed aus–B. aman crop yield was similar to that of the B. aman crop. The low yielding ability of B. aman is an established fact, so it is difficult to obtain satisfactory benefit from a weeding investment in the mixed system. Farmers grow a mixed crop to get an aus crop before flooding and take a chance with the B. aman crop that may be damaged in some years because of the abrupt rise of floodwater.

Weed control in broadcast aman and deepwater rice. B. aman and DWR are grown in fields inundated with various depths of water (50 cm to more than 3 m). In some low-lying areas, deepwater or floating rice is grown where flooding reaches 4–5-m depth. The seed is sown in dry soil in March and continued up to mid-May with 60–90 kg seed ha^{-1}. Land preparation of this rice becomes easy if a rabi crop is harvested before sowing the seeds. Rice and weed seed germinate together and crop-weed competition is severe at the early stage of crop growth. Farmers generally use the rake to control germinating weeds. If the weather and soil conditions are favorable, 1–3 rakings-ladderings are applied. After that, hand weeding is done. Generally, 2–3 hand weedings are required before the intrusion of floodwater. If weed control is not done, the whole crop may be destroyed.

Good stand establishment of DWR mainly depends on weed control. Weed control prior to inundation will not only produce a good stand but also ensure healthy seedlings having the ability to cope with the rising of floodwater or even flash flood. The major weed species in dryland conditions are *Echinochloa colona*, *Leersia hexandra, Cynodon dactylon, Alternanthera sessilis*, and wild rice, *Hygroryza aristata*. After rainfall, *Cyperus iria, Scirpus articularis, Paspalum scrobiculatum, Commelina diffusa*, etc., begin to grow. On the other hand, after the intrusion of floodwater, weeds such as *Pistia stratiotes, Ipomoea aquatica, Azolla pinnata, Aponogeton crispum, Eichhornia crassipes,* and *Nymphaea* sp. become dominant in standing water (Mamun 1988, Hasanuzzaman 1975, Catling et al 1983). Among the weeds of DWR, the wild rice species are considered to be the most notorious. These are *Oryza perennis* Moench, *O. rufipogon* Griff., *O. spontanea*, and *O. sativa* var. *fatua. O. sativa* var. *fatua* has wide distribution in DWR and possesses the highest flood tolerance among the wild rice. It produces few tillers and has small panicles with 10–15 spikelets having awns. The spikelets shatter easily, even before full maturity, which helps in dispersal of this weed. Most wild rice is perennial and forms a woody rootstock that remains viable for many years. Thus, the wild rice propagates through the awned seeds and root stocks and can quickly infest an area. Other DWR varieties cannot perform well in an area having been heavily infested by wild rice. Farmers grow jute or purple-leaf rice cultivars to facilitate the removal of wild rice (Hasanuzzaman 1975). In the past, it was recommended to puddle fields every 4–5 years to control the buildup of wild rice (Alim et al 1962). B. aman fields require repeated weeding after the use of raking-laddering. This involves high costs to control weeds.

Labor costs for different field operations, including hand weeding in the DWR crop in Bangladesh monitored by Hoque et al (1981), are shown in Table 6. A total of 447 h ha^{-1} were spent in hand weeding, which accounted for 56% of the total for the field operations of DWR.

Table 6. Labor and cost requirements for different field operations in farmers' deepwater rice crop in Bangladesh.

Field operation	Labor requirement		Cost of labor	
	($h\ ha^{-1}$)	(%)	(US$ ha^{-1})	(%)
Land preparation	133	17	18	16
Seeding	4	0.5	<1	<1
Weeding	447	56	60	52
Harvesting	799	100	114	100

It was calculated that farmers spent about US$60 ha^{-1} for weed control, which was about 52% of the total labor costs required for all field operations. The total cultivation cost of DWR was about $162 ha^{-1}, 37% of which was spent for weed control. However, farmers mostly used available family labor.

Floating weeds cause serious economic loss to B. aman and DWR. DWR seems to be quite sensitive. It has been observed that segregated plants of DWR or fields with poor stand can be easily overcome by naturally growing aquatic weeds. The transparency of water and intensity of sunlight penetrating into water may be the two major factors for the germination and subsequent growth of aquatic weeds. DWR with a good stand cut the sunlight to effectively reduce weed germination. Long, broad, and droopy leaves of DWR seem to be a good character for this purpose (Ahmed 1975). Protective barricades or hedges of tall plants such as jute, *dhaincha (Sesbania aculeata)*, or floating bamboo poles are often used to keep out the mass of floating aquatic weeds such as water hyacinth. Large masses of water hyacinth from rivers or deeper haors may intrude into the rice field by the wind or water current and damage the crop completely. Therefore, protective measures against water hyacinth are most essential in many situations.

Weed control of DWR is tedious, time-consuming, and quite costly. Intervention with modern weed control practices is essential. Upland rice herbicide may be tested in the dry period of crop growth, which may reduce costs and effectively control dryland weeds. The selection of varieties having a high competitive ability against weeds and cultural practices for reducing weed infestation need to be tested in DWR.

Weed control in boro rice (lowland irrigated rice). Boro rice, an irrigated crop, is increasing in flood-prone areas at the expense of B. aman rice. Shallow-flooded fields in which water recedes early mean that farmers turn to a rabi crop. After harvesting the rabi crop, boro seedlings are transplanted in January and February. In the medium-flooded areas, boro is also grown after harvesting the rabi crop. In deep to very deep flooded areas, however, a sole boro crop is grown either in the whole area or at the periphery of the depression. In these fields, after transplanting of boro seedlings, *Cyperus difformis* and *C. iria* grow in abundance. Within 30 days, weeds such as *Echinochloa crus-galli*, *Jussiaea repens*, *Scirpus* sp., *Marsilea quadrifolia*, *Ipomoea reptans*, and *Paspalum scrobiculatum* begin to compete with the boro rice. In deep to very deep flooded areas, boro is grown after the floodwater recedes. In late

October and November, when the floodwater recedes considerably, the fields are cleared of aquatic weeds and are then left undisturbed until the optimum depth for transplanting of seedlings is reached. At the early stage of growth, weeds cannot create much of a problem because of the presence of sufficient water, but, with the gradual decrease in water from the fields, the weed problem intensifies. If weeds are not properly controlled, the spaces between the rice hills are covered with aquatic weeds such as *Monochoria hastata, Scirpus juncoides, Jussiaea repens, J. octovalvis, Echinochloa crus-galli, Sagittaria guyanensis, Cyanotis axillaris,* etc. Other aquatic weeds such as *Ceratophyllum demersum, Aponogeton crispus, Ipomoea aquatica, Limnanthemum indicum, Paspalum* spp., *Ottelia alismoides, Lemna trisulca, Sagittaria sagittifolia, Hygroryza aristata, Enhydra fluctuans, Ceretophyllum demersum, Nymphaea* spp., *Potamogeton indicus, Myriphyllum indicum, Hydrilla verticillata,* etc., also grow in boro rice fields.

It is essential to control weeds timely and properly. Under unweeded conditions, a serious yield loss (30–40%) can occur. Farmers practice weeding, but it is not done properly because of ignorance about appropriate techniques, timing, and various socioeconomic reasons. As a result, yield loss occurs. Mamun (1988) noted an average of about 10% yield loss in both local and modern boro rice because of weed competition (Table 1). Samad et al (1992) observed a greater yield loss in indigenous varieties than in modern ones. They observed a higher competitive ability of modern varieties against weeds than local ones in this agroecological situation.

The cost of weed control varies among varieties and other factors, including labor availability. The present practice of weed control is mostly hand weeding and use of a rotary weeder. The cost of weed control generally varies from Tk 2,500 to 3,500 per ha of land.

Various means are available for controlling weeds in boro rice. Some of the important ones follow.

Hand weeding. Generally, two hand weedings are required for boro rice. The first hand weeding is required at 3–4 weeks after transplanting (WAT) and the second hand weeding at 6–7 WAT. If the crop is kept weed-free for the first 50 days after transplanting, further weed control has no significant effect on yield loss.

Flooding. If the fields are kept flooded at a water depth of 10–12 cm a few days after transplanting, this reduces the growth of weeds. This is not applicable where irrigation water is costly. But, it is feasible where abundant water is available.

Push-type rice weeder. The Japanese rice weeder and the BRRI-developed weeder are used in boro rice. The Japanese weeder has two sets of rotary tines for action on weeds. The BRRI weeder has a drum fitted with tines that is effective in controlling young weed seedlings but not full-grown weeds. The weeder controls weeds within rows and the space between plants remains unweeded, which requires hand cleaning. A weeder is generally used two times to control weeds. A hand weeding is done to remove weeds close to the rice hills after the first operation with a weeder. The cost of subsequent hand weeding decreases greatly when a push-type weeder is used.

Table 7. Summary results on the performance of three preemergence herbicides in weed control in boro rice, BRRI, Gazipur.

Herbicide	Weed biomass (g m^{-2})	Grain yield (t ha^{-1})
Argold 10EC (cimethylin) at 75 mL ai ha^{-1}	20.54	5.82
Aim 40WG (carfentrazon methyl) at 25 g ai ha^{1}	17.20	5.69
Arozin 30EC (anilofos) at 40 mL ai ha^{-1}	22.20	4.93
Ronstar 25EC (oxadiazon) at 1 ai ha^{1}	32.27	4.66
Two hand weedings	19.10	5.72
No weeding	139.84	2.51

Herbicide. Herbicide is now gaining popularity among farmers. Farmers seldom used herbicides 5–10 years ago because weeding labor was abundant. More recently, the labor requirement in the nonagricultural sector has been increasing considerably. Now, labor has become costly and in the peak weeding period labor scarcity becomes acute. So, many farmers have started to choose herbicides as an alternative to hand weeding for effective weed control at a low cost. Now, a few brands of herbicide are available in the market in either liquid or granular form. The herbicides are mostly preemergence and after application little or no additional hand weeding is required. Table 3 lists herbicides used in rice fields. Ronstar 25EC (oxadiazon), Setoff 20WG (cinosulfuron), and Golter 5G (butachlor) are effective and economical in controlling weeds in lowland rice. In direct wet-seeded rice, Ronstar 25EC and Setoff 20WG control weeds satisfactorily. Many herbicides were tested in boro rice from 1997 to 1999 at BRRI. Argold 10EC (cimethylin), Aim 10EC (carfentrazon ethyl), and Arozin 30EC (anilofos) showed a better performance in weed control and gave a grain yield comparable with that of hand weeding (Table 7).

Future research directions

Weeds are undoubtedly a serious problem in rice grown in the flood-prone environment. The current practice of weed control in dry-sown rice is hand weeding, which is laborious and expensive. Herbicide may be an alternative to hand weeding before flooding but there is still a need to protect the crop from water-borne weeds after flooding. Therefore, all pertinent factors that affect the weed problem in aus and DWR should be taken into consideration to develop effective weed control practices. Considerable research results on control of weeds in boro rice are available, but little is known about biological control. Therefore, in the current situation, the following activities need proper attention:

- Monitoring the current weed problem
    - Weed survey and weed seed bank in soil
    - Yield loss assessment

- Cultural practices affecting weed infestation
  This is very important for dry-sown rice and the following practices/field conditions should be studied:
  - Current tillage practice
  - Seed rate
  - Fertilizer application
  - Current flooding pattern and soil moisture in nonflooded conditions
  - Postharvest field operations
  - Cropping pattern
- Studies on the biology of problematic weeds
- Weed control studies. Since weed species and control practices vary from place to place, weed control studies need to be conducted in farmers' fields. The following weed control practices need priority attention:
  - Mechanical
  - Chemical
  - Biological
  - Integrated

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Challenges and strategies in managing rice for higher productivity in the flood-prone environment: arthropod and vertebrate pest management in Bangladesh

Z. Islam and D. Catling

Deepwater rice (DWR) is grown on the floodplains and deltas of Bangladesh. Its coverage has declined from 2.09 million ha to about 0.80 million ha since the late 1960s, mainly because of an expansion of the irrigated boro (winter rice) crop. Deepwater rice hosts a large complex of arthropods (74 insects, one crab, and a snail) and three vertebrate (two rats and a bird) pests. More than 40 species of parasitoids and a similar number of arthropod predators were identified from DWR fields. Among the pest complex, yellow stem borer, *Scirpophaga incertulas* (Walker) (Pyralidae); bandicoot rats, *Bandicota bengalensis* (Gray & Hardwick) and *B. indica* (Bechstein) (Rodentia); and rice hispa, *Dicladispa armigera* (Olivier) (Chrysomelidae), are major pests. The rice mealy bug, *Brevennia rehi* (Lindinger)(Pseudococcidae); pyralid leaffolders (three species); the ear-cutting caterpillar, *Mythimna separata* (Walker) (Noctuidae); flea beetle, *Chaetocnema basalis* Baly (Chrysomelidae); acridid and tettigonid grasshoppers (11 species); field cricket, *Euscyrtus concinnus de Haan*; and rice thrips *Stenchaetothrips biformis* (Bagnall) (Thripidae) are sporadic pests. Yellow stem borer is well adapted to the aquatic DWR environment and its population increases rapidly during the flooding period. It is a chronic pest and it causes on average about 20% yield losses. Bandicoot rats are good swimmers and are also adapted to the aquatic environment. They concentrate on village islands at the onset of flooding and later move to flooded DWR fields and make nests out of cut DWR or water hyacinth stems. Rat populations and damage vary greatly among locations and years. High populations of rats can cause more than 60% yield losses but average loss is about 5–6%. The succulent, elongating DWR plants are attractive to rice hispa. The ear-cutting caterpillar was the most destructive pest of DWR in the past, but expansion of irrigated boro rice at the expense of DWR seems to have reduced its incidence. Rice leaffolders, grasshoppers, and field crickets are present in DWR fields throughout the season, but outbreaks do not usually occur. Rice thrips, mealy bugs, and flea beetles are not adapted to the aquatic environment and thus are troublesome only in the preflood period. The incidence of mealy bug in DWR was first recorded in 1979 and flea beetle in 1977. The economic importance of these sporadic pests is not well understood. Available management options for the major pests and future management strategies are discussed.

Deepwater rice (DWR) is a special rice adapted to areas flooding from 50 to 400 cm and it includes traditional tall plant types and the true floating rice. The floating DWR plant has the unique ability to elongate with the rise of floodwater. In the wet season, DWR is virtually the only crop that can be grown in such an environment. Based on the flooding pattern, the crop growth period can be divided into preflood, flooding, and flood recession periods. In the preflood period, DWR grows as rainfed lowland rice. The onset of flooding transforms the plant as the elongating stem keeps its terminal part above the rising water level. In that period, rapid vegetative growth takes place and the stem become soft and succulent, which is suitable for certain pests. Elongated plants bend upward during the flood-receding period, keeping the terminal part upright by the formation of a knee on the upper nodes. The crop is usually harvested after the flood recession, often in dry field conditions. The crop is usually established by broadcasting dry seed. However, DWR crop establishment by transplanting is also being practiced in some areas under the boro-DWR pattern.

Deepwater rice is mainly grown on the floodplains and deltas of the Meghna, Jamuna, and Ganges river systems. In a typical year, 30% of the net cultivated area floods deeper than 1 m and DWR is grown on these seasonally flooded lands (MPO 1987). Before the 1970s, DWR was one of the most important rice crops of Bangladesh, occupying about 20% of the rice lands and contributing about 14–16% to the total rice production (Ahmed 1974, Hasanuzzaman 1974). Major DWR areas are concentrated in the central parts of the country, though DWR is grown throughout the country, with the exception of the greater Patuakhali District. However, DWR coverage had shrunk from 2.09 million ha in the late 1960s to about 0.80 million ha at the beginning of the 21st century.

The arthropod and vertebrae pest complex

Extensive surveys undertaken in Bangladesh by the authors during the late 1970s and less frequently in the 1980s revealed a large complex of flora and fauna in the DWR environment, including 74 insects, two rodents, one crustacean, one snail, and one bird as pests of DWR in Bangladesh (Table 1). A large complex of leaf eaters and leafhoppers dominates the list but most of them are minor pests or have little economic significance. Among them, yellow stem borer (YSB), rice hispa (RH), and two species of bandicoot rats are considered as major pests, and seven others—mealy bug, ear-cutting caterpillar (ECC), a complex of leaffolders (LF) and grasshoppers, field cricket, flea beetle, and thrips—are considered as sporadic or localized pests (Tables 1 and 2).

The DWR agroecosystem shows a seasonal succession of dominant flora and fauna mainly determined by hydrological changes from preflood, flood, and flood recession (Catling and Islam 1999). The preflood period is conducive to moderate buildups of canopy-living insects (Table 2), whose numbers are limited by the synchronous planting of large areas, the sparse stands, poor plant condition, and robust weeding practices (Catling 1992). Flooding profoundly influences the composition, population structure, and density of flora and fauna in DWR fields. The numbers of

Table 1. List of arthropod and vertebrate pests of deepwater rice in Bangladesh.

Common name	Scientific name	Family: order
Insect pests		
Rice stem borers	*Scirpophaga incertulas* (Walker)	Pyralidae: Lepidoptera
	Chilo polychrysus (Meyrick)	Pyralidae: Lepidoptera
	Sesamia inferens (Walker)	Noctuidae: Lepidoptera
Rice leaffolders	*Cnaphalocrocis medinalis* (Guenee)	Pyralidae: Lepidoptera
	Marasmia patnalis Bradley	Pyralidae: Lepidoptera
	M. exigua (Butler)	Pyralidae: Lepidoptera
Rice caseworm	*Nymphula depunctalis* (Guenee)	Pyralidae: Lepidoptera
Ear-cutting caterpillar	*Mythimna separata* (Walker)	Noctuidae: Lepidoptera
Rice skipper	*Pelopidas mathias* (Fabricius)	Hesperiidae: Lepidoptera
Hairy caterpillar	*Psalis pennatula* Fabricius	Lymantriidae: Lepidoptera
Green semilooper	*Naranga diffusa* Walker	Noctuidae: Lepidoptera
Green horned caterpillar	*Melanitis lede ismene* Cramer	Satyridae: Lepidoptera
Swarming caterpillar	*Spodoptera mauritia* Boisd.	Noctuidae: Lepidoptera
Common cutworm	*Spodoptera litura* Fabricius	Noctuidae: Lepidoptera
	S. cilium Guenee	Noctuidae: Lepidoptera
Old world bollworm	*Helicoverpa armigera* Hubner	Noctuidae: Lepidoptera
Greasy cutworm	*Agrotis ipsilon* Hufnagel	Noctuidae: Lepidoptera
Hairy caterpillar	*Creatonotos gangis* Linnaeus	Arctiidae: Lepidoptera
Rice whorl maggot	*Hydrellia* sp.	Ephyridae: Diptera
Leaf miner	*Pseudonapomyza asiatica* Spencer	Agromyzidae: Diptera
Rice seedling fly	*Atherigona* spp.	Muscidae: Diptera
Rice gall midge	*Orseolia oryzae* (Wood-Mason)	Cecidomyiidae: Diptera
Rice hispa	*Dicladispa armigera* (Olivier)	Chrysomelidae: Coleoptera
Flea beetle	*Chaetocnema basalis* (Baly)	Chrysomelidae: Coleoptera
	Tanymecus indicus Faust	Curculionidae: Coleoptera
	Monolepta signata Olivier	Chrysomelidae: Coleoptera
	Myllocerus blandus Faust	Curculionidae: Coleoptera
Root weevil	*Hydronomidius molitor* Faust	Curculionidae: Coleoptera
	Altica caerulea Olivier	Chrysomelidae: Coleoptera
Rice grasshoppers	*Oxya chinensis* (Thunberg)	Acrididae: Orthoptera
	O. hyla intricata (Stal)	Acrididae: Orthoptera
	O. japonica japonica (Thunberg)	Acrididae: Orthoptera
	Acrida exaltata Walker	Acrididae: Orthoptera
	Ailopus thalassinus tamulus Fabricius	Acrididae: Orthoptera
	Gesonula punctifrons Stal	Acrididae: Orthoptera
	Trilophidia annulata (Thunberg)	Acrididae: Orthoptera
	Atractomorpha psittacina psittacina (de Haan)	Pyrgomorphidae: Orthoptera
	A. cernulata crenulata (Fabricius)	Pyrgomorphidae: Orthoptera
	Eucomocephalus incertulas (Walker)	Tettigonidae: Orthoptera
	Conocephalus longipennis (de Haan)	Tettigonidae: Orthoptera
Field cricket	*Euscyrtus concinnus* (de Haan)	Gryllidae: Orthoptera
Mole cricket	*Gryllotalpa africana* Palisot de Beauvois	Gryllotalpidae: Orthoptera
Rice thrips	*Stenchaetothrips biformis* (Bagnall)	Thripidae: Thysanoptera

continued

Table 1. Cont.

Common name	Scientific name	Family: order
Green leafhoppers	*Nephotettix virescens* (Distant)	Cicadellidae: Homoptera
	N. nigropictus (Stal)	Cicadellidae: Homoptera
Orange-headed leafhopper	*Thaia oryzivora* Ghauri	Jassidae: Homoptera
White leafhopper	*Cofana spectra* (Distant)	Cicadellidae: Homoptera
Zig-zag leafhopper	*Recilia dorsalis* (Motschulsky)	Cicadellidae: Homoptera
Maize orange leafhopper	*Cicadulina bipunctata* (Meliahar)	Cicadellidae: Homoptera
	Empoascanara simillima Dworakowska	Cicadellidae: Homoptera
	Hecalus porrectus (Walker)	Cicadellidae: Homoptera
	Balclutha hortensis Lindberg	Cicadellidae: Homoptera
	B. micropterus Pruthi	Cicadellidae: Homoptera
	B. saltuella (Kirschb.)	Cicadellidae: Homoptera
	Kolla mimica Distant	Cicadellidae: Homoptera
	Exitianus indicus (Distant)	Cicadellidae: Homoptera
	Empoascanara truncata (Ahmed)	Cicadellidae: Homoptera
	Ratbura nagpurensis (Distant)	Cicadellidae: Homoptera
	Deltocephalus motatus Pruthi	Cicadellidae: Homoptera
	Aconeurella prolixa (Lethierry)	Cicadellidae: Homoptera
	Cicadula maculatus Pruthi	Cicadellidae: Homoptera
Brown planthopper	*Nilaparvata lugens* (Stal)	Delphacidae: Homoptera
Whitebacked planthopper	*Sogatella furcifera* (Horvath)	Delphacidae: Homoptera
	Opiconsiva dodona (Fennah)	Delphacidae: Homoptera
	Nisia atrovenosa Distant	Meenoplidae: Homoptera
	Oliarus hodgarti Distant	Cixiidae: Homoptera
Rice aphid	*Hysteroneura setariae* (Thomas)	Aphididae: Homoptera
Rice mealy bug	*Brevennia rehi* (Lindinger)	Pseudococcidae: Homoptera
Rice bugs	*Leptocorisa acuta* (Thunberg)	Alydidae: Hemiptera
	L. oratoria (Fabricius)	Alydidae: Hemiptera
Ear-head shield bug	*Menida histrio* (Fabricius)	Pentatomidae: Hemiptera
	Cymodema basicornis (Motsch.)	Lygaeidae: Hemiptera
	Paromius piratoides Costa	Lygaeidae: Hemiptera
	Cymoninus turaensis (Paiva)	Coreidae: Hemiptera
Noninsectan arthropod pests		
Crab	*Sartoriana spinifera* (Wood-Mason)	Crustacea
Snail	*Pila pesmei* (Morlet)	Pilidae: Mollusca
Vertebrate pests		
Greater bandicoot rat	*Bandicota indica* (Bechstein)	Rodentia
Lesser bandicoot rat	*B. bengalensis* (Gray & Hardwick)	Rodentia
Purple moorhen (kaim)	*Porphyrio porphyrio* Linnaeus	Aves

Sources: Catling (1980), Islam et al (1996), Islam (1989b).

many arthropods decline sharply and aquatic communities quickly establish. Populations of some leafhoppers, all planthoppers, and many leaf eaters decrease and remain at low levels for the rest of the crop season. However, the presence of succulent DWR stems and leaves and milder weather extremes are favorable for a few pests.

Table 2. Status of insect and vertebrate pests of deepwater rice with main period of activity in Bangladesh.

Insect and vertebrate pests	Prefloodᵃ	Flooding	Receding
Major			
Yellow stem borer	+	++	++
Bandicoot rats	+	++	++
Rice hispa	++	++	
Sporadic or localized			
Mealy bug	++	+	
Ear-cutting caterpillar			++
Leaffolders	+	+	+
Grasshoppers	+	+	++
Field cricket	+	+	+
Flea beetle	++		
Thrips	++		
Minor			
Dark-headed borer	+		+
Pink stem borer	+		+
Rice skipper	+		+
Rice caseworm	+	+	
Rice swarming caterpillar	+		+
Rice bugs			+
Rice whorl maggot	+	+	
Leaf miner	+	+	
Leafhoppers	+	+	+
Brown planthopper	+	+	
Rice gall midge	+	+	
Seedling flies	+		
Mole cricket	+		
Armyworm			+
Birds		+	+

[a] + = low incidence, ++ = moderate to high incidence
Source: Catling and Islam (1999).

Some pests reappear in the flood-receding period but remain in low numbers, while a few other pests can become important at the end of the season or after flowering (Table 2).

Ecology of major and sporadic pests

The ecology and damage potential of major and sporadic pests differ from each other and these are now discussed briefly.

Yellow stem borer

The yellow stem borer (YSB), *Scirpophaga incertulas* (Walker) (Pyralidae: Lepidoptera), is a chronic pest of DWR (Catling and Islam 1995, Catling et al 1984-85, Islam 1994). YSB has been associated with cultivated rice for thousands of years (Yasumatsu 1976), and probably evolved within a broad belt stretching from northern India to North Vietnam, where rice is endemic. It lives exclusively on rice and a few wild *Oryza* species. The highly specific insect-host plant relationship and special aquatic adaptations suggest that YSB may have originated in the DWR environment (Catling and Islam 1982).

Eggs are laid in clusters on the leaf blade. The first-instar larva briefly feeds on the leaf sheath before boring into the stem. Larvae are mostly solitary (Catling et al 1984-85, Islam 1994). During the plant elongation stage, larvae and pupae remain inside the stem, often below the water level, and moths can emerge through the water. Pupation is always in the stem lumen, typically 1–2 cm above a node. During summer, the egg, six larval instars, pupa, and total life cycle last for an average of 8.4, 25.4, 9.1, and 46 days, respectively, and adults live on average for 5.4 days (Islam and Catling 1991). Diapause during the winter extends the larval period from 25 to 92 days (Islam 1993).

There are normally six annual field generations but, in a year of prolonged winter, there may be five generations (Islam 1991a, 1993). The first generation lives in boro rice, the second to fourth and/or fifth on DWR, and mature larvae of the fifth and/or sixth generation remain in diapause in DWR and transplant-aman rice stubble. Diapause is induced by photoperiod and terminates by cumulative day degrees above a minimum development threshold temperature (15 ^{o}C).

The major factors influencing population density are weather extremes, natural enemies, plant condition, and flooding (Catling and Islam 1999). Succulent elongating stems during the flooding period are suitable for penetration, feeding, and survival for neonates and thus the population often increases rapidly. High temperatures (>34 ^{o}C) combined with low humidity (<70% relative humidity) are lethal, causing high egg and neonate mortality (Suwongwan and Catling 1987), which reduces population densities during the preflood period. Egg parasitism by six parasitoids (Table 3) kills 41–64% of the eggs in broods 2–6. Although 21 larval or larval-pupal parasitoids and a mermithid nematode were found to be active in the DWR environment (Table 3), larval parasitism was estimated to be less than 10% and pupal parasitism about 24% (Islam 1992). The effect of predation is difficult to estimate and thus the extent is uncertain. Longhorn grasshopper (*Conocephalus longipennis* de Haan) accounts for about 8% of YSB eggs (Islam et al 1996). Eighteen recognized major generalist predators are present in DWR fields (Table 4).

Key factor analysis revealed that on average about half of the eggs are destroyed by parasitoids, 96% of young larvae fail to penetrate the stems (key mortality factor), while 39% of the remaining larvae and 27% of the pupae succumb within the stem (Islam 1994). Egg mortality and losses of young larvae are weakly density dependent, thus making YSB a chronic pest. Characteristic damage, such as death of the central leaf whorl (deadheart) at the vegetative stage and death of the growing panicle (whitehead), may cause a significant yield reduction.

Table 3. Parasitoids and nematode parasites of deepwater rice insect pests found in the deepwater rice environment in Bangladesh.

Family: order	Scientific name	Host insect pest
Egg parasitoids		
Eulophidae: Hymenoptera	*Tetrastichus schoenobii* Ferriere	Yellow stem borer
Mymaridae: Hymenoptera	*Anagrus* spp.	Leaf- and planthoppers
	A. optabilis (Perkins)	Leaf- and planthoppers
Pteromalidae: Hymenoptera	*Eupteromalus parnarae* Gahan	Stem borers
Scelionidae: Hymenoptera	*Telenomus rowani* Gahan	Yellow stem borer
	Gryon sp.	Stem borers
Trichogrammatidae: Hymenoptera	*Trichogramma japonicum* Ash.	Yellow stem borer
	T. pallidiventris Nagaraja	Stem borers
Larval or larval-pupal parasitoids		
Bethylidae: Hymenoptera	*Goniozus* sp.	Stem borers and leaffolders
Braconidae: Hymenoptera	*Agathis* sp.	Stem borers
	Cotesia (Apanteles) flavipes Cam.	Stem borers and leaffolders
	A. schoenobii Wilkinson	Stem borers and leaffolders
	Cotesia sp.	Stem borers
	A. argiope	–
	Bracon chinensis Szep.	Stem borers
	Microchelonus sp.	Stem borers
	Orgilus sp.	Stem borers
	Rhaconotus sp.	Stem borers
	Scutibracon hispae Viereck	Rice hispa
	Shirakia schoenobii Viereck	Stem borers
	Stenobracon nicevillei (Bingham)	Stem borers
Chalcididae: Hymenoptera	*Brachymeria megaspila (Cam.)*	Lepidopterous leaf eaters
	B. podagrica (F.)	Lepidopterous leaf eaters
	B. albotibialis (Ashmead)	Lepidopterous leaf eaters
	B. secundaria (Rus.)	Lepidopterous leaf eaters
	Brachymeria	Lepidopterous leaf eaters
Elasmidae: Hymenoptera	*Elasmus claripennis* Cam.	Stem borers and leaffolders
Eulophidae: Hymenoptera	*Tetrastichus ayyeri* Rohwer	Stem borers
Eurytomidae: Hymenoptera	*Eurytoma* sp.	Stem borers
Ichneumonidae: Hymenoptera	*Amauromorpha sp.*	Stem borers
	Charops sp.	Yellow stem borer
	Isotima javensis (Rohwer)	Stem borers and lepidopteran leaf eaters
	Isotima sp.	Stem borers
	Temelucha philippinensis (Ash.)	Stem borers and lepidopteran leaf eaters
	T. stangli (Ashmead)	Stem borers and lepidopteran leaf eaters
	Xanthopimpla flavolineata Cam.	Stem borers and lepidopteran leaf eaters
	Xanthopimpla sp.	Leaffolders
Platygasteridae: Hymenoptera	*Platygaster* sp.	Stem borers and lepidopteran leaf eaters
Pteromalidae: Hymenoptera	*Eupteromalus parnarae*	Stem borers
Mermithidae: Hymenoptera	Mermithid nematode	Stem borers
Tachiniidae: Diptera	*Sturmiopsis inferens*	Stem borers
Sarcophagidae:	*Sarcophaga* sp.	Stem borers

Source: Catling (1980).

Table 4. List of arthropod predators of insect pests of deepwater rice in Bangladesh.

Family/order	Common name	Scientific name	Prey
Coenagriidae: Odonata	Damsel fly	*Agriocnemia pygmaea* (Rambur) *A. lactiola* Selys *Ceriagrion coromandelianum* (F.) *Enallagma* sp. *Ishnura aurora* Brauer *Pseudagrion* sp.	Stem borer moths, lepidopteran leaf-eating caterpillars, nymphs and adults of leaf- and plant-hoppers, and adult gall midge
Libellulidae: Odonata	Dragon fly	*Acisoma panorpoides* Rambur *Brachythemis contaminata* (F.) *Neurothemis tullia* (Drury)	
Tettigoniidae: Orthoptera	Longhorn grasshopper	*Conocephalus longipennis* de Haan	Lepidopteran eggs
Dermaptera	Earwig	*Labidura riparia* (Pallus)	Lepidopteran pest larvae
Miridae: Hemiptera	Mirid bug	*Cyrtorhinus lividipennis* Reuter	Plant- and leafhopper eggs and nymphs
Anthcoridae: Hemiptera	Anthcorid bug	*Orius tantillus* (Motsch.)	Lepidopterous leaf eaters, nymphs of hoppers and thrips
Reduviidae: Hemiptera	Plant bug	*Sirthenea flavipes* Stal	Lepidopterous larvae
Formicidae: Hymenoptera	Ants	*Monomorium* sp. *Pheidole* sp.	Stem borers
Cicindelidae: Coleoptera	Tiger beetle	*Cicindela minuta* Olivier	Voracious pests
Carabidae: Coleoptera	Ground beetles	*Casnoidea indica* (Thunb.) *Chlaenius xanthospilus* Wied. *C. quadricolor* (Olivier) *Colliuris fuscipennis* (Chd.) *Diplocheila polita* (F.) *Drypta flavipes* Wied.	Lepidopteran larvae and pupae
Staphylinidae: Coleoptera	Rove beetle	*Paederus fuscipes* Curtis	Plant- and leafhoppers, stem borer
Coccinellidae: Coleoptera	Lady bird beetle	*Brumoides suturalis* (F.) *Chilocorus* nr. *politus* Muls. *Scymnus nubilus* Muls. *Micraspis discolor* (F.)	Plant- and leafhoppers, lepidopteran pest larvae, thrips, aphids, and coccids
Chloropidae: Diptera		*Anatrichus pygmaeus* Lamb.	Rice mealy bug, stem borer larvae
Tetragnathidae: Araneae	Long-jawed spiders	*Tetragnatha javana* (Thorell) *T. vermiformis* (Emerton)	Stem borer and leaf eater moths, plant- and leafhoppers
Lycosidae: Araneae	Wolf spider	*Lycosa annandalei* Gravely	Plant-and leafhoppers
Clubionidae: Araneae	Sac spiders	*Clubiona japonicola* Boes. & Str.	Stem borer and leaf eater moths
		Clubiona sp.	Plant- and leafhoppers
Thomisidae: Araneae	Crab spider	*Thomisus cheranpunjius* Tikader	Stem borer moths
Salticidae: Araneae	Jumping spider	*Bionor* sp.	

Bandicoot rats

The black field rat, *Bandicota bengalensis* (Gray and Hardwicke), and large black field rat, *B. indica* (Bechstein), are the most destructive vertebrate pest of DWR. They cut DWR stems starting from the maximum tillering stage before flooding and again from the flood peak until crop harvest. They bite open the leaf sheath to feed on the growing shoots, causing terminal leaves to die, and produce a deadheart; stems are cut off 2–4 cm above the water (Islam et al 1993). They live in the DWR fields during the dry season and move to the raised village islands with the onset of flooding. However, both species are strong swimmers and as the flood levels stabilize they swim back to the DWR fields to make nests out of cut DWR stems or water hyacinth, where they remain active until the floods recede (Poche et al 1980). When the water has receded, they dig elaborate burrow systems up to 9 m long and cut panicles, in which they hoard on average 1.7 kg of rice (60 kg ha^{-1}) (Ahmed et al 1986). Besides rice, rats feed on snails, crabs, insects, water lily stems and fruits, water hyacinth stems, and algae.

Several predators—mongooses, civet cats, snakes, foxes, owls, and hawks—predate on rats. Food availability, preflood rainfall, flooding pattern, and intra- and interspecific competition (Poche et al 1980) regulate their populations. Greater rat activity occurs in years of drought or late flood.

Rice hispa

Rice hispa (RH), *Dicladispa armigera* (Olivier) (Chrysomelidae: Coleoptera), first recorded in DWR by Butler (1919), emerged as a serious problem in the early 1980s. The grub is a leaf miner, while the adult is an external leaf feeder. So far, only a few natural enemies have been found to predate or parasitize RH. A braconid (*Scutibracon hispae*) parasitizes up to 50% of the grubs in DWR. Although it is an ancient localized pest, little critical work has been done on the insect.

Rice hispa are prevalent in swampy tidal areas in the southwestern coastal districts where they breed on tidal wetland and DWR ratoons during winter (Karim 1987). Adults are strong fliers and are believed to disperse over long distances to the north and east. They attack boro, aus, DWR, and T. aman in sequence. Rice hispa prefer young plants to older ones, and the succulent leaves of elongating DWR are very favorable.

Rice mealy bug

Rice mealy bug, *Brevennia rehi* (Lind.) (Pseudococcidae: Homoptera), was first observed in DWR during the preflood period in 1979 (Catling 1980) and later reported to be severe in years of drought during the preflood period. The nymphs settle between the leaf sheath and stem and suck large quantities of plant sap. Infested plants first become chlorotic and then brown and stunted. Although mealy bugs are killed by submergence, infested plants do not recover and are unable to elongate as the water rises. The highest populations usually develop at shallow-flooded sites where inundation tends to be late and in drought years where flooding is delayed. More than half of the nymphs may be parasitized, mainly by encyrtids. Many common grasses and rice weeds serve as alternate hosts (Williams 1970).

Ear-cutting caterpillar

Ear-cutting caterpillar (ECC), *Mythimna separata* (Walker) (Noctuidae: Lepidoptera), the most serious pest of DWR in the past, has declined in prevalence over the last three decades. This may be linked to the shift from rainfed to irrigated rice cropping. The nocturnal larvae conceal themselves under litter and vegetation, and are particularly active at dusk and dawn. Instars V and VI may become gregarious, cutting the panicles and completely devouring the plants in an outbreak area; they then swarm and migrate to a new area. Pupation takes place in an earthen cell. A wide range of grasses serve as alternate hosts. Natural enemies include larval and pupal parasitoids (three tachinids and two ichneumonids), bacterial disease, and a virus (Alam 1965). There are five annual generations, with the population reaching its highest seasonal densities in October-November when conditions are favorable, which may cause severe outbreaks in ripening DWR. Analysis of historical data revealed that drought and early flood recession usually precede outbreaks. A review of regional data suggested that sporadic outbreaks might originate from moths migrating into Bangladesh from south and central India on the southwest monsoon (Dean 1979).

Rice leaffolders

Three leaffolder (RLF) species—*Cnaphalocrocis medinalis* (Guen.), *Marasmia patnalis* Bradley, and *M. exigua* (Batler) (Pyralidae Lepidoptera)—with similar life histories (Pathak and Khan 1994) attack DWR in Bangladesh. *Cnaphalocrocis medinalis* is more common than the other two *Marasmia* spp. The presence of rice leaffolder damage symptoms (folded leaves) is common in DWR fields, usually at low numbers. RLF damage may reach a moderate level during the flooding and flood-receding periods, but serious outbreaks usually do not occur. The population reaches its highest level during September-November (Islam et al 1996). RLF prefers varieties with broad leaves (Islam and Karim 1997). The effect of the characteristic leaf damage and folded leaves that occur throughout the DWR season on grain yield is less understood. Rice leaffolders have 5–6 annual generations, with populations reaching the highest level in October. The large complex of parasitoids and predators active in rice fields usually keeps the RLF population at a low level (Islam et al 1996).

Field cricket

Field cricket, *Euscyrtus concinnus* de Haan (Gryllidae: Orthoptera), adults and nymphs defoliate rice plants by eating cut-out areas in the central portions of leaves to leave just the midrib and leaf margins. Populations are usually low before flooding but increase during the flooding period to outnumber shorthorn grasshoppers by the end of the season. Populations may reach moderate levels during the flooding and flood-receding periods, but serious outbreaks are rare (Catling and Islam 1999). Biology and pest status are little understood. The role of natural enemies is not clear.

Flea beetle
A black flea beetle, *Chaetocnema basalis* (Baly) (Chrysomelidae: Coleoptera), is the most abundant coleopteran leaf eater in DWR in Bangladesh (Catling 1980). It was first recorded in Bangladesh during the 1977 survey of DWR. A small, shiny black beetle with massive rear femora enabling it to jump vigorously when disturbed, it is commonly present in the preflood period when populations may reach moderate or sometimes outbreak levels (Catling and Islam 1999). Populations may persist during flooding, but in low numbers. Adult feeding produces narrow, white longitudinal lesions on both sides of the leaves, which may lead to severe leaf tattering. The life history and the role of natural enemies are not known.

Rice leaf thrips
The rice leaf thrips, *Stenchaetothrips biformis* (Bagnall) (Thripidae: Thysanoptera), is a minute insect. Larval and adult feeding cause yellowing and curling of leaf tips and then a rolling of the leaf blade longitudinally. It is mostly present during the preflood period and continues into the early flooding period. Thrips are more abundant in years of drought, when damaged patches can be quite common in some DWR fields. Thrips are also present on DWR in the flooding period, but in much lower numbers. Other than rice, thrips also infest maize, sugarcane, other graminaceous crops, and weeds. After the flowering of DWR and T. aman rice, they migrate to grasses to hibernate. In spring, they multiply on these weeds or other graminaceous crops (wheat, barley) and from there they move back to rice. The role of natural enemies in population regulation is not known.

Grasshoppers
A complex of seven species of shorthorn grasshoppers, two longhorn grasshoppers, and two katydids is active in Bangladesh DWR (Table 1). Grasshoppers are present in almost all rice fields throughout the DWR season but, so far, no outbreaks have been recorded. Shorthorn grasshoppers are more prevalent in the preflood period than longhorn grasshoppers; all shorthorn grasshoppers are nonswarming species and are well adapted to the DWR environment. Eggs are laid in the soil in the normal situation, but, with flooding, eggs are laid between the rice stem and leaf axils above the water level. The nymphs are semiaquatic with their hind legs adapted for swimming. Grasshopper adults and nymphs feed on leaf tissue from the edge of the leaf blade. The significance of natural enemies is not clear.

Impact of major pests

The effects of yellow stem borer and bandicoot rat damage on crop growth and grain yields were studied in detail in Bangladesh, whereas the effect of rice hispa on grain yield is poorly understood and the effects of most sporadic pests are unknown.

Yellow stem borer

Before flooding, about half of the infested DWR stems show the characteristic deadheart symptom (Catling et al 1984-85, Islam 1990a), whereas with flood very few infested stems show deadhearts. The ratio between infested stems and deadheart is 1:6 in early elongation and 1:13 in the booting to flowering stage; the ratio between whiteheads and infested stems is also wide (1:10 to 1:19). Thus, deadhearts and whiteheads grossly underestimate infestation levels. Moreover, some of the whiteheads remain enclosed in the leaf sheath and are thus overlooked in field counts (Islam 1990b). Average stem infestation reaches 35–44% by the late ripening stage. Crop loss assessments using potted plants in the field and in water tanks, floating exclusion cages, insecticidal checks, the marking of plants in the field, and the sampling of infested and healthy plants at maturity all indicated that DWR on average suffers about 20% yield losses from stem borer attack (Catling et al 1987, Islam 1990a). The mechanism of crop loss involves (1) the loss of bearing stems because of deadheart and whitehead production, (2) the loss of apparently healthy but infested stems in rising floodwater, and (3) a decrease in filled grain numbers and individual grain weight. Considering its consistent and chronic abundance throughout DWR areas and the extent of yield loss, YSB may be considered as the number-one pest of DWR.

Bandicoot rats

Many Bangladeshi farmers rate rats as the second most important pest of DWR (Catling and Yasin 1981). Damage is low during the preflood period: significant stem cutting begins toward the end of elongation and continues into the ripening stage. Damage varies greatly among fields and years. Surveys revealed that 34–83% of fields suffer some damage. Bandicoot rats bite open and eat the growing shoot, cut stems above the water level, and finally cut maturing panicles, which they store in burrow systems (Islam et al 1993). It was estimated that they store on average about 58 kg ha^{-1} or 6% of the crop (Ahmed et al 1986). Field exclusion experiments in two successive years of high rat populations produced on average 47% higher grain yields in a set of fenced plots compared with unfenced plots (Islam et al 1993). DWR seems to suffer on average about 5–7% yield losses and these are more severe when high populations occur.

Rice hispa

Serious outbreaks of rice hispa occurred from 1981 to 1986 in all rice crops in Bangladesh, including DWR (Karim 1987). Detailed yield loss studies have not been conducted. A pot experiment indicated high yield losses from severe leaf damage at the basal tillering stage, followed by gradual flooding (52% loss), mainly because of the loss of bearing stems, while damage at the elongation stage reduced yields (27% loss) because of reduced panicle weight (Islam 1989a). Severe leaf damage at the elongation stage coinciding with rapid water rise reduces elongation ability and submerges stems (Islam 1991b). Since hispa is sporadic and the relationship between damage levels and yield losses has not been well established, it is difficult to estimate average yield losses.

Ear-cutting caterpillar

The ear-cutting caterpillar has the potential to cause severe losses within a very short period before detection. This can happen in one night after the initiation of panicle cutting (Alam 1975). Severe outbreaks were reported from 1939 to 1973 (Alam and Chowdhury 1977); in 1969, 0.5 million ha were infested and 50,000 ha severely damaged (Alam 1975). Since then, severity has declined probably because of the major increase in irrigated paddy at the expense of DWR (Catling and Islam 1999).

Management prospects

The DWR environment and its pests are difficult to manage. Flooding produces long fragile stems several meters in length. The plant then collapses during the flood recession period, making access to the field difficult and damaging the crop. The entangled plant mass makes the adoption of normal pest management practices extremely difficult and nearly impossible. The low economic value of the crop further discourages researchers and farmers from developing and adopting specific pest management options. Nevertheless, limited research has shown that some cultural, mechanical, and chemical control opportunities can be considered for the management of some pests. Natural biological control is at the core of pest management in DWR; therefore, the conservation of natural enemies is vital and the indiscriminate use of hazardous pesticides must be avoided at all costs. The use of pesticides in DWR poses additional dangers to water-body pollution.

Yellow stem borer

Host-plant resistance was investigated as a possible control option. Hundreds of traditional DWR varieties and advanced breeding lines were screened under field and controlled conditions in Bangladesh, Thailand, and India. So far, definite YSB-resistant DWR varieties have not been found, probably because the soft stem becomes highly favorable for larval penetration and development. However, the development at IRRI of transgenic rice with *Bt*, including *Bt* DWR, may represent a new direction in the control of stem borer and other lepidopterous pests.

The entire YSB population remains in diapause in DWR and T. aman stubble from November to the end of January. Simple cultural measures during the dry season such as pulverizing, burning, or sun heating of straw and stubble could drastically decrease the vulnerable off-season population, which is the nucleus of later outbreaks (Table 5). One well-timed spray application of insecticide (monocrotophos) targeting the 5th brood moth peak in August to mid-September with a motorized knapsack sprayer from the side of a boat was found to reduce yield losses significantly (Islam et al 1988). A spray threshold of 75 YSB female moths and egg masses per 10 minutes of counting was suggested. However, the adoption of such a technology in the DWR environment is not ecologically desirable on a wide scale.

Table 5. Available management options and future strategies for management of major insect and vertebrate pests of deepwater rice in Bangladesh.

Pest	Management options	Future strategy
Yellow stem borer	Reduction of diapausing population in winter through management of DWR and T. aman stubble—burning (in field or homestead), plowing, sun-dry, etc., by end of January Application of insecticide (monocrotophos) targeting 5th brood moth peak in August to mid-September at 75 female moths and egg mass per 10 minutes of scouting[a]	Development of resistant varieties by incorporation of *Bt* gene in popular DWR varieties
Bandicoot rats	Poison baiting in village islands at early phase of flooding[b] Rat trapping during flooding and flood recession period by using live traps baited with snail flesh or paddy grains on raft of banana trunk Fumigation of active burrows before flooding and after flood recession by aluminum phosphide	Simultaneous adoption of these techniques likely to reduce rat problem
Rice hispa	Collection and destruction of adults by sweepnetting before flooding Clipping of leaves with high population of grubs and/or eggs at early tillering stage Nitrogen topdressing of infested fields before flooding (for recovery) Application of insecticides targeting high adult populations[a]	Management of nucleus hispa population in endemic areas by integration of different methods

[a]Will cause water pollution, thus avoid wide-scale adoption. [b]Take extreme care to avoid poisoning of children and animals. **Note:** Natural biological control is at the core of DWR pest management; thus, insecticide sprays should be avoided as much as possible.

Bandicoot rats

Farmers employ locally made traps and poison baits while the Bangladesh Department of Agriculture Extension organizes an annual month-long rat eradication program, which may account for several million rats. Branches are sometimes placed in the field by farmers to encourage predation by owls (Poche and Miah 1986). The possibility of varietal resistance was unsuccessfully explored in Thailand (Catling and Islam 1999). Intensive poison baiting can effectively reduce (87–94%) rat populations confined in island villages during the early phase of flooding (Table 5)(Poche and Miah 1986). However, the technique has a high risk of poisoning humans, especially children, and domestic animals. A new approach, the use of live traps baited with snail flesh or paddy grains placed on rafts from early flooding, was found to be effective in trapping bandicoot rats in DWR fields (Islam and Karim 1995). Trapping effectively reduced stem and panicle cutting and cut yield losses. Although the success of rat control measures depends on concerted efforts, individual farmers were still able to benefit from this method. Fumigation of active burrows with aluminum phosphide before flooding and after flood recession also reduced rat populations.

Rice hispa

Sweeping with nets is practiced in some areas of Bangladesh and is effective if carried out on a large scale and continued until hispa numbers decrease. Sweeping in DWR fields, however, is only feasible before flooding (Table 5). The clipping of infested leaves 3–4 cm above the ligule may remove most of the eggs and grubs (Karim 1987). Scattered late planting should be avoided as young growth is more attractive to hispa beetles. Nitrogen topdressings before flood may stimulate the recovery of damaged plants. Most sprayable rice insecticides are effective against adult rice hispa but can be used only before flooding. Aerial sprays were applied for hispa outbreaks from 1960 to 1973 (Khan 1975). An economic threshold level has yet to be developed for DWR.

Ear-cutting caterpillar

Alam (1965) recommended the burning of rice straw and stubble, plowing to expose larvae and pupae to birds, flooding of infested fields, the use of perches for predatory birds, planting of early maturing varieties, and the use of simple light traps to reduce moth numbers. But the effectiveness of these measures has not been tested. The pest is effectively controlled by the application of carbaryl, chlordane, dicrotophos, fenthion, malathion, and methoxychlor, whereas dichlorvos is the most effective. Both aerial and ground sprays are effective. Aerial sprays were made from 1956 to 1973.

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Rice diseases in the flood-prone ecosystem and their management

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In Bangladesh, the total area of deepwater rice (DWR) and a vast area of T. aman and boro fall under the flood-prone ecosystem. Among the major constraints, disease is one of the most important for rice production in this ecosystem. Among the diseases, ufra, sheath blight (ShB), blast, and tungro are the most important ones causing considerable yield losses. In the past, ufra was restricted to the deepwater ecosystem, but, now, this disease affects all rice crops. Yield loss varies depending on disease severity and may reach 100% in some cases. This disease is found in 18 districts of Bangladesh. Ufra could be controlled by the integration of crop rotation, stubble cleaning or burning, alternate wetting and drying, deep plowing, soil amendment with neem-seed dust, and avoiding growing seedlings in infested fields. The application of nematicide under the carbofuran group is also effective. Sheath blight disease is found throughout the country. It can cause up to 31% yield loss. Panicle initiation to the booting stage of the rice plant is the most susceptible stage for this disease. There is no resistant variety for it. It could be managed by some cultural practices, such as burning of infected straw and stubble in the field, planting seedlings at wider spacing, using balanced fertilizers, etc. Some fungicides are also effective against this disease. A study shows that blast disease could reduce yield by 11% to 46.4% under low to moderate disease severity. Leaf blast is the major problem in the boro season, whereas node and neck blast are major problems in the T. aman season. Several BRRI-released varieties are resistant to this disease. Other measures to protect from the disease include collection of seed from disease-free fields, avoiding the excess use of nitrogenous fertilizers, keeping standing water in the field, and using effective fungicides. Tungro is a virus disease transmitted by the green leafhopper (GLH). Under the flood-prone ecosystem, T. aman is the most vulnerable to this disease, which can infect the rice plant from the seedling stage. The earlier the infection of tungro, the higher the yield loss is. This disease could be managed by using resistant varieties, destroying infected plants and alternate hosts, and controlling insects by a light trap or insecticides.

Flood is a regular event in Bangladesh although its intensity and durability vary in different years. Since the topography of Bangladesh is not uniform, flooding depths also vary in different locations. According to Allison (1974), about 67,340 km^2 of area have flooding depth higher than 0.3 m, 31,080 km^2 from 0.9 to 1.83 m, and 14,245 km^2 higher than 1.83 m. Most deepwater rice (DWR) is grown in 0.9 to 1.83 m water depth. In 1972-73, the DWR area was 2.02 million ha, which constituted 20% of the total rice area and 16.2% of the total production, and yield averaged 0.8 t ha^{-1} (Ahmed 1974, Sen 1974). DWR is grown in 19 districts of Bangladesh with different intensities, with the most in Faridpur (55.6% of total rice area) and the least in Chittagonj (0.3%) (Ahmed 1974). The DWR area is gradually decreasing because of the increasing cultivation of modern boro rice in that area. The DWR area is now 0.81 million ha, with an average yield of only 0.96 t ha^{-1} (BBS 1998). Besides DWR, a vast area of T. aman and boro also falls under the flood-prone environment. Among the different constraints to yield in the flood-prone ecosystem, diseases are the most important. Among the diseases, ufra, sheath blight (ShB), blast (BL), and tungro are the major concerns for farmers. In this paper, we discuss the importance, epidemiology, symptoms, and management aspects of these diseases.

Ufra disease and its management

Butler (1913) reported the occurrence of ufra disease for the first time in DWR from the then East Bengal (now Bangladesh) and identified the causal nematode as *Ditylenchus angustus* (Butler) Filipjev. Ufra has now spread throughout all rice ecosystems. This disease causes characteristic symptoms on the rice plant. The nematode is an ecto-parasite. It feeds on unemerged leaf sheaths, leaves, and growing buds or growing panicles sitting in between the leaf sheaths at the growing point of the rice plant and multiplies there. A mosaic or chlorotic discoloration of young emerged or emerging leaves or sheaths accompanied by a yellowish or whitish green splash pattern is a characteristic. Later, the damaged area turns brown. At the reproductive stage, three types of symptoms may appear based on the extent of panicle exsertion: ufra I-UI (no exsertion), UII (partial exsertion), and UIII (total exsertion of the panicle).

At the end of the season, the ufra nematode starts coiling and enters into a cryptobiotic state. Normally, it remains coiled until the next spring under the deepwater ecosystem. It may also survive on self-sown rice, ratoons, etc. In a coiled condition, it is capable of retaining its motility for 6 months. When water becomes available, it uncoils and swims to the rice plant and causes infestation. It can cause disease on the rice plant at any stage. However, the severity varies with the stage of the plant at infestation. Disease severity was higher when the plant was inoculated at 15–25 or 55–65 days after sowing (DAS) compared with inoculation at 35–45 DAS (BRRI 1986). Another study revealed that disease severity was more than 94% when the infection started at the earlier stages, that is, at 15–29 DAS. Disease severity decreased with the increase in the age of the plant at infection (BRRI 1990). The reason for such a contradiction regarding plant age and susceptibility might be varietal characteristics. The resistance genes in all the varieties may not be operative at the same stage. Some might show a resistant reaction at the seedling stage, but become susceptible at the adult stage. For example, Rayada 16-05-2 showed a resistant reaction at the seedling and maximum tillering stages but was susceptible at the maturity stage. Rayada 16-07-1, on the other hand, showed a moderately resistant reaction at the seedling stage, was resistant at the maximum tillering stage, and was moderately susceptible at the maturity stage (BRRI 1990). Miah (1974) opined that ufra disease every year affects at least 2% of the 2 million ha of DWR in Bangladesh. He also reported that, in 1972, about 200 ha of DWR in Matlabganj *thana* was affected by this disease. It is one of the most devastating diseases. Yield loss varies depending on the severity of the disease and the loss may reach 100% in some cases (Miah and Bakr 1977). Catling (1979) reported an estimated 4% average yield loss of DWR because of ufra disease.

Monitoring of the disease in some parts of Narshingdi (Dhaka), Chandina (Comilla), Matlab (Comilla), and Hajiganj (Comilla) from 1977 to 1983 revealed that the status of the disease in most areas remained unchanged or decreased to some extent. A recent survey indicated that this disease occurred in epidemic proportion in the T. aman season in Faridpur District among other nonflood-prone districts. In Faridpur, about 20 ha of T. aman fields were totally damaged (Anonymous 1999). Ufra disease is found in 18 districts of the country in all rice seasons (Fig. 1).

Some varieties/lines were found to be resistant to this disease when inoculated artificially. Progenies developed through crosses using Bazail 65 or Rayada 16-06 as resistant sources revealed that in the F_6 generation 14 lines of DWR type and seven lines with modern plant types were resistant to ufra disease (BRRI 1994). Table 1 shows a list of resistant varieties/lines.

Management of ufra by phytosanitary methods such as crop rotation, stubble burning, alternate drying, and deep plowing has been recommended for a long time. Stubble cleaning was also found to reduce the disease significantly. Considerable reduction of the disease was also observed by amending the soil with neem-seed dust at 0.5 kg ha^{-1}. The intensity and severity of ufra disease could be reduced by delaying the sowing time or transplanting DWR (Tables 2 and 3) (BRRI 1980, 1981). Experimental results show that using carbofuran at 1.5 kg ai ha^{-1} at the time of broadcasting or transplanting could control ufra disease. Only transplanting was as effective as using carbofuran with broadcast seed (BRRI 1982). In a broadcast field, disease incidence was the highest (77.2%); it declined to about 58% when carbofuran was applied. However, under transplanting conditions without any nematicide, disease incidence was about 53%. The incidence decreased to a large extent with a yield increase when carbofuran was used along with transplanting (Table 4). In the boro and T. aman seasons, the use of carbofuran at 0.75 kg ai ha^{-1} significantly reduced the disease and increased yield (BRRI 1993). Ufra disease was more severe in wet years and in areas where flood arrived early and the crop was harvested late. This indicates that the length of the overwintering period regulates the survival of the nematodes from one season to another. This partly explains the reason for lower disease incidence in a late-sown crop or in a transplanted field. The length of the overwintering period of the ufra nematode is a critical factor in its survival from one season to another. Pro-

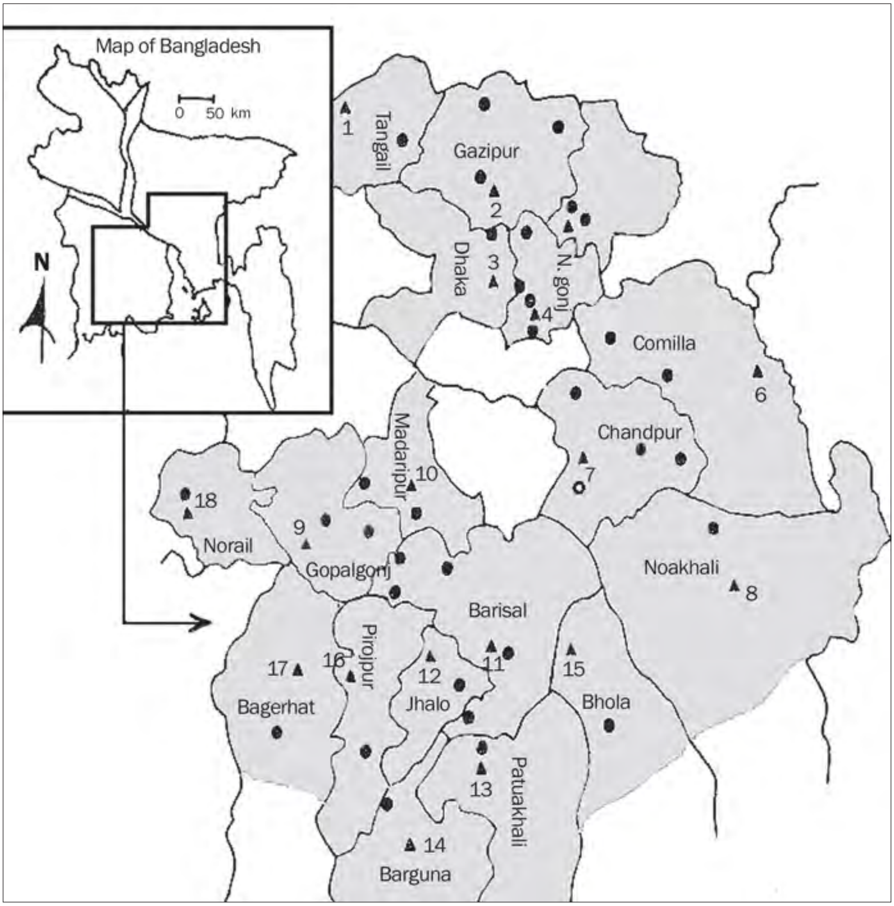

Fig. 1. Map of Bangladesh showing the 18 districts where ufra is found.

longing that period by either delaying the sowing time or transplanting is suggested as a method of control (Mc Geachie and Rahman 1982). Infested seedlings are the most efficient carriers of this pathogen. Growing of seedlings in a field previously infested with ufra disease will obviously infest the new seedlings and should be avoided. Disease severity is higher and consequent yield lower in soil deficient in Zn or S (BRRI 1980, 1985). Therefore, correction of the soil deficiency by applying Zn or S helps reduce disease severity. Soil amendment with Ca-silicate and rice husk increased silicon content in the leaf sheath of both resistant and susceptible cultivars and in stems of only resistant cultivars. Ufra infestation decreased because of the increase in silicon content in the leaf sheath, suggesting that cultivar susceptibility can be reduced in the case of both resistant and susceptible cultivars through the application of silicon in the soil (BRRI 1990).

Table 1. Some rice varieties/lines with resistance against ufra disease under artificial inoculation.

Variety	Line	
	Tall plant type	Modern plant type
Habiganj Aman I	IR63142-J6-B-1-1	IR63174-J1-B-1
Bajal Dhan	IR63142-J8-B-2-1	IR63174-J1-B-3-2
Khoya motor	IR63142-J8-B-2-2	IR63174-J1-B-2-3
Khama 1106	IR63153-J9-B-1-1	IR63174-J1-B-4-3
Khama 55/22	IR63188-J8-B-1-1	IR63174-J1-B-6-3
BR306-B-3-2	IR63188-J8-B-2-1	IR63174-J2-B-4-2
BR523-168-3	IR6188-J8-B-7-1	IR63174-J3-B-1-2
Rayada 16-06	IR6188-J8-B-7-2	
Rayada16-06-1	IR63225-J2-B-1-1	
Rayada 16-07-2	IR63225-J2-B-4-1	
Rayada 16-09-1	IR63225-J2-B-4-2	
Bazail 65	IR63225-J2-B-6-1	
CNL-319	IR63225-J2-B-6-2	
	IR63645-J3-B-9-1	

Table 2. Effect of delayed establishment of broadcast aman on ufra development in farmers' fields at Matlab, 1980. Random sampling of 25 stems per plot.

Treatment	% ufra-infested stems at different sampling dates			
	15 Jul	7 Aug	23 Aug	15 Sep
Broadcast 19 Feb	20	24	52	24
Broadcast 6 March	8	2	52	34
Broadcast 21 March	2	2	22	2
Transplanted 16 April	0	0	16	0

Source: BRRI annual report (1980).

Table 3. Effect of delayed sowing of mixed aus and deepwater rice (DWR) or transplanting of DWR on disease development and yield, Matlab, 1981.

Planting method	Date	% ufra-infested panicles	Yield (kg ha^{-1})		
			Aus	DWR	Total
Broadcast	5 March	13.2	520	1,030	1,550
Broadcast	15 March	8.2	454	1,360	1,814
Broadcast	25 March	4.6	229	1,293	1,522
Transplanted	20 April	7.4	–	1,696	1,696
CV%			19.3	16.8	15.0

Source: BRRI annual report (1981).

Table 4. Efficacy of carbofuran in controlling ufra disease in deepwater rice.

Treatment	Ufra disease incidence (%)	Healthy panicles (%)	Yield (t ha^{-1})
Broadcast seed	77.2	20.7	0.24
Broadcast seed + carbofuran	58.3	40.4	0.44
Transplanted	52.9	44.4	0.59
Transplanted + carbofuran	36.7	60.6	0.94

Source: BRRI annual report (1982).

Table 5. Effect of time of transplanting during T. aman on sheath blight development and yield of rice (var. BR11) under inoculated conditions. Each figure is the average of nine hills.

Planting date	Av. disease incidence	1,000-grain wt (g)	% unfilled grain	Yield (g $hill^{-1}$)
17 Jul	5.3	18.9	49.1	9.3
1 Aug	4.3	21.9	32.8	14.9
16 Aug	3.4	21.4	17.9	17.5
31 Aug	2.2	22.0	24.0	16.0
15 Sep	2.3	19.8	37.8	14.1

Source: BRRI annual report (1993).

Sheath blight disease and its management

ShB disease is generally a concern for T. aman rice under the flood-prone ecosystem. ShB is a fungal disease caused by *Rhizoctonia solani*. In the early 1970s, it was considered to be a minor problem for rice cultivation. But, after the introduction of modern, high-nitrogen-responsive rice varieties, the intensity and severity of this disease increased gradually. Dense and luxuriant growth of the plants and warm humid conditions favor disease development. This is now one of the most devastating diseases of rice and it is distributed throughout the country. The pathogen as sclerotia survives in the soil for a long time. Mycelium in the infected plant tissues also serves as a primary source of the inoculum. So far, thousands of varieties, germplasm accessions, and breeding lines have been tested against *R. solani* and none was found to be resistant to this disease. However, the intensity and severity of the disease were found to vary with transplanting time (Table 5). In the T. aman season, disease severity and subsequent yield loss were higher if the crop was transplanted before the first week of August (BRRI 1993). This disease generally starts at the maximum tillering stage of the plant and later. The panicle initiation to booting stage was found to be the most vulnerable stage for this disease. Close spacing and the use of high nitrogenous fertilizer favor the rapid increase in this disease. The yield loss from ShB disease was estimated to be up to 31% under natural disease incidence (Shahjahan et al 1986).

Table 6. Sheath blight development and yield of rice at different levels of hill inoculation at the maximum tillering stage in the T. aman season, 1999.

% hill inoculation	% increase in hill infection	% RLH	Yield (t ha^{-1})	% yield loss over control
	15.8	0.57	3.83	–
5	41.3	8.47	3.60	6.0
10	54.0	14.87	3.44	10.2
20	45.0	22.98	3.09	19.3
40	33.8	18.03	3.03	20.9

Recent studies revealed that the rate of spread of the disease was higher when 10% of the hills were infected at the maximum tillering stage compared with 5%, 20%, and 40% hill infection. Yield loss at 5%, 10%, 20%, and 40% hill infection at the maximum tillering stage was 6.0%, 10.2%, 19.3%, and 20.9%, respectively (Table 6). The inoculum spreads through irrigation water, rainwater, or flood and causes infection in new fields. Once introduced to a field, it remains there year after year.

When the soil is puddled for transplanting, the inoculum in the soil, especially the sclerotia, floats on the water surface and comes in contact with the rice plant. The infection does not begin until the maximum tillering stage, when the plant canopy covers the entire field. This is because the pathogen needs high temperature and high humidity for its growth and development. Such conditions do not prevail before the maximum tillering stage. The disease begins at the water line on the leaf sheath and the affected area first becomes greenish gray and water-soaked. The shape of the lesion is ellipsoid to ovoid; later it becomes irregular. An individual spot enlarges up to 2 to 3 cm and becomes grayish white with brown margins. Later, several lesions coalesce, resulting in leaf death. The lesion may extend to the leaf blade and all the leaves of a plant may be blighted, resulting in plant death.

The pathogen is soil-borne and also survives in infected plant debris and acts as a primary source of inoculum. It is therefore suggested to burn the plant residue in the field after harvesting of T. aman rice. Planting with wider spacing favors adequate ventilation in the rice field, which helps keep the disease below a damaging level. Although there are no resistant varieties, plants with a tall stature were found to have some tolerance for this disease and this type of plant should be planted in endemic areas. Alternate wetting and drying of fields and the use of balanced fertilizer reduce disease severity. In endemic areas, T. aman rice should be planted after the first week of August. Integration of all these cultural practices is suggested to manage the disease and reduce yield loss. Besides cultural practices, some fungicides were found to be effective against this disease. These include the spraying of Tilt twice at 500 mL ha^{-1} at 15-d intervals or Homai or Topsim M at 2 kg ha^{-1} at panicle initiation to booting stage. ShB disease begins as a cluster in the field (Mia et al 1997); therefore, it is not necessary to spray the whole field.

Blast disease and its management

Blast is another important disease under the flood-prone ecosystem in the T. aman and boro season. It is important because of its wide distribution, rapid spread, and destructiveness under a favorable environment. The causal agent of this disease is *Pyricularia grisea*. This pathogen can cause disease at any stage of the crop, from seedling to maturity. If the variety is susceptible and the environmental conditions are favorable, it can cause complete damage to the crop. However, information on the exact yield losses from this disease is scarce. The amount of loss by panicle blast is greatly influenced by the time of infection. The earlier the infection, the higher the yield loss is. Leaf blast causes stunting of plants and reduces the number of mature panicles, 1,000-grain weight, the weight of brown rice, etc. The time of infection and other factors were found to influence disease severity and eventually yield. Few reports are available on yield losses from blast disease of rice in Bangladesh. In a chemical control study, the disease caused yield losses of about 11% in one location and 46.4% in another location under low to moderate disease severity (Shahjahan et al 1987). The disease spreads from infected seeds, diseased plant debris, and alternative hosts.

The blast endemic areas of Bangladesh are Sunamganj, Kishoreganj, Netrokona, some parts of Dhaka, Chittagong, and Satkhira. Up to the mid-1960s, blast disease of rice was a major constraint to rice production. During the 1980 boro season, the disease broke out in almost all regions of Bangladesh. Severely affected varieties were Chandina, IR8, Pajam, and Pusa II. BR8, BR9, and Pajam also had neck blast. Among the other environmental factors, cultivation of susceptible variety Pajam for three consecutive seasons was considered to be the main factor (Miah et al 1980). Another outbreak of leaf blast and neck blast occurred in Bangladesh during the 1990 boro season on both local and modern rice varieties. A survey of eight greater districts of Bangladesh revealed that the disease incidence and severity ranged from 1% to 100%. Relative humidity and rainfall in 1990 were higher than in the previous year. The cultivars grown in different regions had not changed during the last few years. Therefore, the reason for this outbreak appears to be related to the weather (Shahjahan et al 1991). Because of the change in cultivation practices and varieties, blast disease now occurs in isolated pockets where susceptible varieties are grown. Leaf blast is most prevalent during the boro season, especially in the seedbed. Under nonepidemic conditions, seedlings survive and are transplanted in the main field along with the inoculum, where under favorable conditions the pathogen attacks the node and panicle base, causing enormous losses. Most times, the collar of the leaf blade is also affected, causing the leaf blade to break off. A similar occurrence of the disease also takes place during the T. aman season. However, neck blast is the major problem in the T. aman season. Under farmers' field conditions, Pajam, IR50, and Akhnisail (a local variety) generally suffer from severe infection. According to Shahjahan et al (1991), epidemics of blast have been recurring in Bangladesh every 3 or 4 years.

Blast disease affects different parts of the rice plant and as such is known by different names, such as leaf blast, node blast, and neck or panicle blast when it occurs on the leaf, node, and panicle, respectively. It also produces lesions on panicle branches and grain. Leaf spots are typically elliptical with more or less pointed ends. The center of the spots is usually gray or whitish and the margin is usually brown or reddish brown. Both the shape and color of the spots, however, vary depending on environmental conditions, the age of the spots, and the degree of susceptibility of the rice variety. The spots usually begin as small, water-soaked, whitish, grayish, or bluish dots. They enlarge quickly under moist conditions on susceptible varieties and remain grayish for some time. Spots on susceptible varieties growing under moist shaded conditions show very little brown margin. On highly resistant cultivars, only minute brown specks of a pinhead size may be observed. The development of brown color usually indicates either a resistant varietal reaction or the existence of weather conditions unfavorable for disease development.

When the node is infected, the sheath pulvinous rots, becomes brown, and usually breaks apart, remaining connected by the nodal septum only. All parts above the infected node die.

Brown lesions are produced near the panicle base, causing neck rot symptoms. When infection takes place at the early stage of grain filling, all the spikelets become sterile and this looks like whitehead symptom from a distance. But, if infection occurs at the later stage, the panicle breaks down. In the field, the junction of the leaf blade and leaf sheath is affected at the later growth stages of the plant, causing the leaf blade to fall off.

Most of the time, infected grains remain symptomless. In some cases, elliptical lesions are produced on the husk.

The use of a resistant variety is the cheapest method for controlling the disease. Screening for resistance to blast is a routine program at the Bangladesh Rice Research Institute (BRRI). So far, thousands of varieties, germplasm accessions, and breeding lines have been tested against this disease and many are resistant. Some resistant or moderately resistant BRRI-released varieties for the boro and T. aman seasons are BR3, BR14, BR25, BR26, BRRIdhan 28, BRRIdhan 32, and BRRIdhan 33. As the disease is seed-borne, it is suggested not to collect seed from infected fields. Light soil with low water-holding capacity favors the disease. Therefore, the water-holding capacity of the soil could be improved by adding organic manure. Infected straw and stubble are the source of inoculum and these should be destroyed. Balanced doses of fertilizer should be used. A high dose of nitrogenous fertilizer aggravates the disease. At the initiation of the disease, the field should be irrigated regularly. Among fungicides, Hinosan 50EC, Fundazol 50WP, Homai 80WP, and Topsin-M 70WP were found to be equally effective in controlling the disease.

Rice tungro disease and its management

Rice tungro is one of the most serious and damaging virus diseases in Southeast Asia. Periodic outbreaks have affected thousands of hectares of rice fields in Bangladesh in the past. The incidence and spread of rice tungro disease in the tropics are determined by the dispersal, movement, number, and migration of viruliferous vector insects, such as the green leafhopper (GLH), *Nephotettix virescens* (Ling 1966). Usually, boro rice in this country is free from tungro incidence compared with other crops, mainly because of cool weather conditions that cause high mortality of vector insects. Hibino et al (1978) found that tungro virus is composed of rice tungro spherical virus (RTBV) and rice tungro bacilliform virus (RTBV). Both of them individually can cause infection in plants (Ali and Miah 1990). RTBV alone can cause mild yellowing, whereas RTSV alone can cause mild stunting of plants. But both RTBV and RTSV infection in the same plant can cause severe stunting associated with yellowing discoloration (Hibino and Mariappan 1983).

The appearance of symptoms and yield loss caused by rice tungro disease vary depending on the susceptibility and age of the rice plant, status of the vector GLH population, type of virus (strain), rice variety, and environment. However, some general symptoms are observed. Yellowing of leaves (interveinal chlorosis) begins at the leaf tip and may extend down the blade. Twisting of young leaves, stunting (slight to severe) of plants depending on the growth stage, reduction in tiller number, delayed flowering or panicle emergence, and degeneration of roots may occur. Infected leaves may also be mottled, the leaf angle may become wider, and the texture of the leaf may become stiff.

The following practices can be followed to manage rice tungro disease:

- Cultivation of resistant varieties such as Mala (BR2), Dulabhog (BR5), Progati (BR10), Shahibalam (BR16), and BRRIdhan 32.
- Destruction of infected plants and alternate hosts such as grass and Bawa Dhan (wild rice).
- The use of a light trap to kill vector insects.
- Control of insects by using a sweepnet in the seedbed and in the main field.
- Application of insecticide if one adult per sweep or five adult insects per sweep are found in the seedbed or main field, respectively.
- Chemical control of vector insects by using Diazinon 60 EC at 1.5 L ha^{-1} mixed with 800–1,000 L of water. These control measures need to be carried out collectively by all the neighboring farmers.

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Recommendations

Research directions

This workshop recognized the need for increasing the productivity of rice lands in the deepwater areas where boro rice has replaced traditional deepwater rice (DWR). Management interventions have created environments in favor of growing boro rice in many areas. In Bangladesh, for example, most of the DWR area is covered by the boro-fallow cropping pattern, which has potential for growing two rice crops: boro followed by a DWR. Boro rice has replaced pulse crops and grazing land in many areas. Further, the changes in the ecosystem and crop production system have adversely affected the fish habitat (because of irrigation and pesticide runoff), which was a traditional source of protein and livelihood for people living in the flood-prone areas. Productivity increases and improvements in livelihood in such areas require, among other things, an improvement of the whole system.

The workshop recommended that there is a need for a multidisciplinary team approach for developing recommendations and transferring technologies for flood-prone areas. A community-oriented farmer participatory approach should be used with a focus on livelihood improvement. Research should emphasize the integration of boro rice with traditional deepwater rice as this has potential to increase productivity and net income, particularly for areas with more than 1 meter of flooding depth. The development of short-duration, cold-tolerant varieties for early harvesting of boro may create space for an additional DWR crop. It was recommended that nutrient management for transplanted and relay-cropped DWR should be investigated to assess and improve the capacity of DWR to survive under different flooding and submergence regimes. Research also should explore the potential role of zero or minimum tillage for reducing the turn-around time between boro and DWR. Further, in the DWR-rabi cropping system, available production technologies with improved varieties of nonrice crops should be promoted for increasing the system's productivity in the flood-prone environment. Also, fish culture must be improved in the vast water bodies of the flood-prone areas to enhance farmers' livelihood and protein supply to local communities. Toward this goal, appropriate action should be taken to improve the fish stock and promote sustainable fish culture practices by farming communities.

Crop improvement for deepwater boro

Workshop participants discussed the current status of genetic enhancement for boro as well as deepwater rice and believed that there was a need to gear up work on genetic improvement of DWR varieties. Research should be strengthened to develop modern higher-yielding DWR varieties. The workshop recommended that the strategies should include enhancing the collection, evaluation, and use of traditional cultivars and landraces by studying genotype differentiation on critical traits; improving popularly grown DWR varieties; using marker-assisted selection (MAS) tools for improving breeding efficiency; and incorporating multiple traits such as submergence tolerance and insect and disease resistance. Concerted efforts should be made to develop a facultative type of rice with high ratooning ability, which can be grown as boro rice as well as a DWR crop. This is based on the idea that the onset of floodwater after the harvest of the boro crop will trigger the gene for elongation of the ratoon crop, which will continue to grow as DWR with the rise of floodwater.

Characterization of the flood-prone ecosystem

There is a need to improve our understanding of the flood-prone ecosystem with respect to the variability existing within it. Management interventions are introducing changes in the physical environment, which contributes to changes in biological, social, and economic environments. The workshop recommended that the characterization of the flood-prone ecosystem be improved using geographic information systems (GIS), more importantly to identify areas with a duration and timing of flooding from 50 to 100 cm and to cover all thanas of Bangladesh.

Governance

Participants discussed the subject of governance and recommended that there should be a research program on the deepwater ecosystem in Bangladesh and other countries where it covers a substantial area involving a multidisciplinary research team.

Technology delivery and uptake

The workshop identified several technologies that hold promise for improving the productivity and income of the farming systems in flood-prone areas. It was recognized that efforts should be made to transfer these technologies to farmers in flood-prone areas through appropriate mechanisms. The technologies identified were

1. Cleaning and purification of moderate-yielding local germplasm for wider adoption in similar agroecological niches.
2. Popularization of an ufra control package (transplanting method).
3. Pilot projects on introducing the following to improve mechanization:
    - Stripper-harvester
    - Thresher
    - Dryer
    - Mini rice mill

4. Production technologies for rice + fish, rice + duck, and rice-nonrice production systems wherever applicable.
5. For most technologies, a compact block demonstration with community participation is needed to speed up adoption.

Policy

The successful adoption of technologies often depends on the existence of a favorable policy environment. The workshop recommended that policy support for the following issues is needed for technology uptake in flood-prone areas. It was strongly believed that a decentralized arrangement for the release of varieties is needed through establishing a provision for the testing and release of varieties for specific locations. It was recommended that extension workers should be recruited for vacant positions in DWR areas and special remuneration be given to staff working in such an unfavorable environment. To develop integrated farming systems, special area-based multidimensional projects integrating rice, fish, duck, vegetables, pulses, etc., need to be established.

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