TOWARDS ENHANCED AND SUSTAINED RICE PRODUCTIVITY IN FLOOD-PRONE AREAS OF SOUTH AND SOUTHEAST ASIA

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ABSTRACT

Rice is the major crop in most rainfed and flood prone environments of South and Southeast Asia providing food for millions of subsistence farming families. Rice productivity in these ecosystems is quite low because of the unavailability of high-yielding varieties tolerant of prevailing abiotic stresses. Hydrological conditions are particularly harsh and unpredictable, leading to recurrent floods and sometimes, water deficit stress. Major constraints in these ecosystems include poor initial crop establishment in direct seeded areas, poor survival upon submergence in transplanted rice, and poor yield in stagnant flood and deepwater areas. Our understanding of the constraints and challenges facing farmers in these areas is progressively advancing, and prospects for increasing productivity are becoming increasingly discernible. These scenarios should mainly focus on the development and deployment of resilient high yielding varieties combing tolerance of the most prevailing stresses, accompanied with their proper crop and nutrient management strategies. Combining the submergence tolerance gene Sub1 with tolerance to flooding during germination as well as to longer-term partial flooding will result in varieties that are widely adapted and could subsequently be grown by farmers in vast areas. Management options should then include improving seedling health in the nursery through proper seed rate and nutrient management, proper handling and water and nutrient management upon transplanting, and proper post-flood nutrient management to enhance recovery, tillering and yield. In most of rainfed and flood-prone areas, great potential exists for dry season farming, which could be exploited given initial capital and infrastructure, and proper varieties and management strategies were made accessible to farmers.

INTRODUCTION

Rice is the stable food for over half of the world population and more than 90% of the world's rice crop is produced and consumed in Asia. Rainfed lowland and flood-prone areas in Asia cover about 47 M ha or about 35% of the total area of rice. The predominant feature of these areas is the lack of water control, with drought and flash-floods or submergence as major constraints in rainfed lowlands. Flood-prone areas, on the other hand, are subject to either more frequent flash or temporary floods (submergence); longer-term flooding of 20–60 cm (partial/stagnant, semi-deep), deep water of >100 cm (deepwater rice), or very deep water levels of up to 3 or 4 meters, as in floating rice areas. Average productivity of rice in these areas is very low, averaging only about 2.5 t/ha in rainfed lowland areas, and even much lower in flood prone areas, averaging about 1.5 t/ha (Table 1; Swain *et al.* 2005). This huge gap in productivity of this system compared with the irrigated ecosystem (about 4.9 t/ha) may suggest its prospects to meet the increasing future demands for rice supply. Obviously, improving productivity of this system is becoming ever more essential with the looming food crises and the inability of most developing countries to meet their local demands from international markets because of the high cost and limited supply. However, the accumulated knowledge about these systems and the awareness of their constraints and potential suggests their plausible exploitation to meet these demands. This can be made even at the farm level, through proper germplasm improvement together with integrated management practices and proper cropping patterns.

GERMPLASM IMPROVEMENT FOR FLOOD-PRONE AREAS

These areas usually experience variable levels and types of excess water stress caused by various factors such as direct heavy rains and flooding from adjacent rivers because of high rains in upper catchments or during high tides. This excess water together with the poor or non-existing drainage facilities, create

Table 1. Total area of rainfed lowland and flood-prone areas of major rice producing countries in South and Southeast Asia

Country	Total rice area (m ha)	Rainfed lowland		Flood prone	
		Area (%)	Yield (t/ha)	Area (%)	Yield (t/ha)
India[§]	42.64	30.10	2.40	11.40	1.50
China[§]	33.01	5.60	3.00	0.00	-
Bangladesh[§]	10.24	43.10	4.30	24.10	2.50
Indonesia[§]	10.28	7.80	3.00	6.40	1.70
Thailand[§]	9.27	72.20	1.80	10.40	2.00
Myanmar[§]	4.57	52.80	3.00	14.30	1.50
Vietnam[§]	6.30	23.40	2.00	16.30	1.50
Philippines[§]	3.42	32.00	2.00	2.00	1.30
Cambodia[€]	2.03	6.02	1.39	NA	NA
Nepal[§]	1.41	60.60	2.20	13.30	0.80
Sri Lanka[§]	0.79	14.90	2.50	1.10	1.00
Average yield			2.51		1.53

Source: [§]Swain *et al.* 2005; [€]O. Makara, pers. com.

serious problems to rice and other crops ranging from water logging, stagnant flooding with partial submergence of 20–60 cm for most of the season, to even complete submergence for varying durations and time during the growing season. Various tolerance traits or mechanisms are necessary for high and stable productivity in these areas, and in most cases, more than one tolerance trait is desired. These include tolerance during germination and emergence in areas where direct seeding is practiced, tolerance of repeated flash-floods during vegetative stage and the ability of fast regeneration after prolonged submergence, and tolerance of long-term partial submergence caused by stagnant floods. In some areas, deepwater (>1 m) stagnates for longer durations and only varieties with fast elongation ability could survive these conditions. Currently this deepwater ecosystem is receiving less emphasis because of its low yield potential and also in some countries such as Vietnam; this system is being replaced by dry season rice. For these reasons we will focus our discussion on the other types of excess water stresses.

GERMINATION AND EARLY ESTABLISHMENT

Direct seeding of rice is becoming more popular in most rice producing countries because of its lower labor cost and cultural simplicity. However, farmers in rainfed and particularly in flood-prone areas often face difficulties in adopting this system because of the uncertain flooding after seeding, with the consequent partial to complete crop failure, as rice is highly sensitive to flooding during germination (Yamauchi *et al.* 1993). Farmers are forced to replant their fields, incurring additional costs and running into other problems late in the season, re-transplant older seedlings in standing water into heavily damaged areas, or leave their fields as fallow. Heavy rains or early floods also pose serious problems for transplanted rice in rainfed areas, and early crop establishment through direct seeding may help avoid further damage just after transplanting. Breeding cultivars with higher tolerance of flooding during germination and early seedling establishment will help avoid these problems. Benefits of this trait could also be extended to irrigated ecosystems where flooding after direct seeding can effectively suppress most weeds.

After screening a large set of diverse germplasm from different sources, we identified several lines with substantial tolerance of flooding during germination. These lines provide a platform for further studies and for breeding. We also developed a few populations and identified QTLs associated with tolerance (Angaji *et al.* 2008). Significant progress was also made in unraveling the physiological and molecular bases of tolerance (Ismail *et al.* 2008). Breeding for tolerance of flooding during germination began at IRRI in 2003, using Khaiyan, Khao Hlan On and MA-Zhan Red as donors for this trait and crosses were made with several popular varieties adapted to both rainfed and irrigated ecosystems. Currently, stable breeding lines are being evaluated in the field. Advanced backcross populations were developed and used for mapping QTLs associated with tolerance and six QTLs, some of which were reasonably large, were identified and are being further fine-mapped (Angaji *et al.* 2008). We are attempting to identify QTL- or gene-specific markers linked to these QTLs to accelerate their incorporation into breeding lines and varieties through marker aided backcrossing (MAB).

FLOODING DURING VEGETATIVE STAGE

Complete submergence can also occur any time during the season and for variable durations. All modern high-yielding rice varieties are sensitive to complete submergence or flash-floods of just few days. However, a few tolerant landraces can withstand inundation for up to 2 weeks. The effects of flooding on rice as well as the physiological bases of tolerance were extensively studied in the past two decades and significant understanding of the mechanisms of tolerance was established (Ram *et al.* 2002; Jackson and Ram 2003; Sarkar *et al.* 2006). Plant survival in flooded areas is greatly affected by the characteristics of the floodwater, particularly the level of dissolved gases, irradiance level, and water temperature and turbidity. Among the important plant traits associated with tolerance are the ability to maintain high non-structural carbohydrate concentrations in the shoot before and following submergence, slower growth, and ability to retain high chlorophyll in leaves (Ram *et al.* 2002; Jackson and Ram 2003; Ella *et al.* 2003; Sarkar *et al.* 2006). Carbohydrates remaining after submergence are necessary for recovery growth and correlated better with survival than carbohydrate level before submergence (Das *et al.* 2005). A rapid regeneration following submergence is an advantage to ensure sufficient production of effective tillers and leaf area, both of which are essential for high yield. Rice plants that exhibit only limited elongation during submergence are more tolerant of complete flooding, and those that recover fast can produce higher yield by producing greater number of productive tillers and limiting the delay in maturity caused by flooding.

Over the last few decades, extensive efforts were devoted to develop rice varieties tolerant of complete submergence, but the progress was scant. This is mainly because of the many undesirable traits associated with the landraces used as donors of tolerance. Varieties released so far were not largely adopted by farmers because their yield is low and their grain quality is still below the standards of farmers in these areas. The recent discovery and cloning of Sub1, a major QTL associated with submergence tolerance (Xu and Mackill 1996; Xu *et al.* 2006), helped overcome these difficulties by shortening the breeding cycle and eliminating the undesirable effects of additional unwanted introgressions or linkage drag normally associated with conventional backcrossing. This becomes feasible after the development and use of a marker-assisted backcrossing system that helped to incorporate Sub1 into numerous popular rice varieties (Neeraja *et al.* 2007; Septiningsih *et al.* 2008). Field experiments showed that Sub1 could substantially help in increasing and stabilizing rice yield in areas where flash-flooding is anticipated, and yield advantage of 1–3 t/ha were reported, when compared to varieties lacking this locus. Field experiments involving Sub1 introgression lines conducted in numerous countries in South and Southeast Asia demonstrated enormous improvement of submergence tolerance in all genetic backgrounds and environments tested so far.

Sub1 can provide sufficient protection for 10–15 days of complete flooding based on seedling age and conditions of floodwater (temperature, turbidity, light penetration etc.). However, this level of tolerance is also below that of the original donor variety FR13A. Besides, under certain conditions and years, higher levels of tolerance are desired, particularly when the duration of flooding is longer or the flooding conditions are conducive of greater damage. This is currently being addressed through (1) fine-mapping additional QTLs from FR13A to be combined with Sub1 through MAB, (2) identification and mapping of new sources of tolerance to discover new genes complementary to Sub1, (3) identification of genotypes with faster recovery ability to minimize the delay in flowering and maturity caused by submergence and to pace the development of productive tillers after flooding, and (4) develop management strategies that could enhance Sub1 tolerance and promote faster recovery.

LONGER-TERM PARTIAL FLOODING

Prolonged partial flooding at 30–60 cm water depths reduces rice productivity in vast areas of rainfed lowlands, and sometimes occurs following short-term complete submergence. Modern rice varieties are not adapted to these conditions and their yield is severely reduced because of high mortality, lower tillering, reduced panicle size, and high sterility. This type of flooding received less attention in the past despite the enormous yield losses and the large area affected. In recent years, efforts were devoted to screen large sets of diverse rice germplasm to identify genotypes with reasonable level of tolerance. Only one-third of the accessions tested so far, showed high survival and produced filled grains when partially flooded with a water depth of about 60 cm through maturity. To our surprise, most of the modern varieties showed high mortality, low tillering ability and poor yields under these partial flood conditions. This is probably why farmers in affected areas still rely on growing low-yielding local landraces. Our understanding of the bases of tolerance of these conditions is still inadequate; however our preliminary data showed that tillering ability under partial flooded conditions is highly correlated with plant survival but was not directly related to spikelet fertility.

Recently large numbers of rice accessions are being screened to identify highly tolerant genotypes to be used in breeding and for further studies, and to discover important traits associated with tolerance. During 2007 DS and WS, screening of a large set of germplasm under stagnant flooding conditions showed that partial flooding of 60 cm water depth through maturity affects plant height, tiller number, spikelet fertility, yield and survival; however, some genotypes showed better tolerance of these conditions (Ismail *et al.* 2008). We also observed that plant survival was better when water levels were gradually increased in contrast to the conditions when water level was rapidly increased to 60 cm. The mean tiller number and percentage reduction also differed based on the type of flooding (Table 2).

Initial testing of Sub1 introgression lines showed that these lines are not particularly successful when subjected to partial flooding following complete submergence. This triggered us to conduct a series of experiments to test whether the poor performance is related to Sub1 or because of other factors. In one experiment, we used the first pair of near isogenic lines, Swarna and Swarna-Sub1, together with IR42 (intolerant check), and three other Sub1 lines (IR40931, IR49830-7, FR13A). These lines were first subjected to flash folding for 12 days, then to three levels of stagnant flooding of 2-5 cm (control), 15-20 cm and 25-30 cm water depth through flowering during 2006 dry season (DS) (Singh *et al.* 2007; 2008). Another experiment was conducted under 30 cm and 50 cm of partial flooding during both DS and WS of 2007, but without exposure to complete submergence.

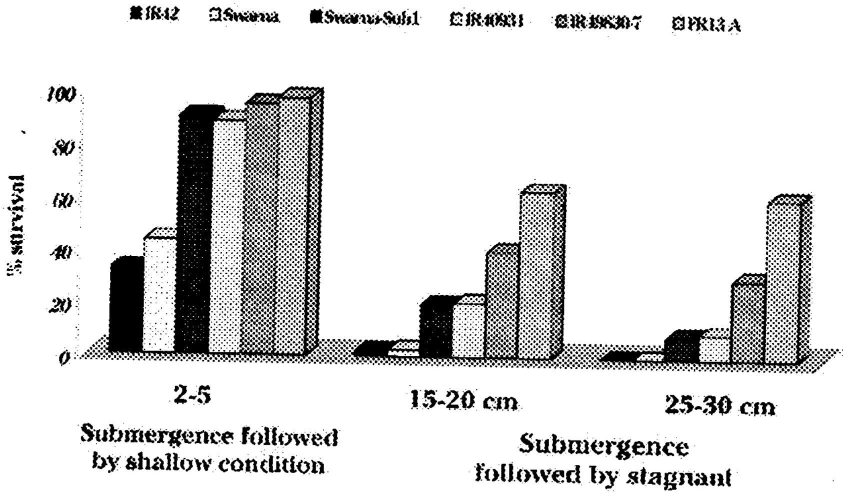
The survival of all genotypes decreased considerably under stagnant flooding following complete submergence (Picture 1), and the reduction was substantially more severe when the genotypes were exposed to stagnant flooding of 25-30 cm than to 15-20 cm of water depth.

Mean grain yield also decreased progressively with increasing water depth (Table 3). Swarna-Sub1 produced 1.4 t/ha over that of Swarna under shallow

Table 2. Stagnant flooding screening of germplasm at IRRI in 2007

Stress conditions	**Season & water depths**	**No. of entries**	**% Survival classes (No. of accessions)**	**% Reduction in tillers Mean tiller no./plant (Control; flooded)**
Severe	**2007 WS** Flooding began 30 DAT with water levels at 20 cm; 37 DAT (40 cm); 42 DAT (60 cm) maintained to maturity	241	90% to 100% (0) 61% to 89% (25) 31% to 60% (56) 0% to 30% (160)	70.6% (32; 9.4)
Gradual	**2007 DS** Flooding began 30 DAT with water levels at 20 cm; increasing by 5 cm weekly to 60 cm until maturity	233	90% to 100% (55) 61% to 89% (101) 31% to 60% (87) 0% to 30% (45)	62.5% (32; 12)

flooding. Under 15-20 cm, grain yield of Swarna was reduced to only 0.30 t/ha and that of Swarna-Sub1 to 2.04 t/ha. At 25-30 cm of stagnant flooding, Swarna failed completely while Swarna-Sub1 showed a drastic reduction in grain yield (0.77 t/ha). The taller and highly tolerant genotypes FR13A and IR49830-7 exhibited less reductions in grain yield amounting to 0.3 and 1.5 t/ha under 15-20 cm and 0.6 and 2.5 t/ha under 25-30 cm of stagnant flooding, respectively, compared with their yield under shallow conditions. The higher survival and yield of these two genotypes could either be a consequence of their height or probably due to other genes that are not related to Sub1.



Picture 1. Percent survival under stagnant flooding following 12 days of complete submergence, 2006 DS.

Table 3. Grain yield during 2006 DS and 2007 DS under different stagnant flooding regimes

Genotype	Grain yield (t/ha)			Grain yield (t/ha)		
	Control	Stagnant water after complete submergence		Control	Stagnant water	
	2–5 cm	15–20 cm	25–30cm	2–5 cm	30 cm	50 cm
IR42	3.42	0.22	0	5.04	4.99	2.36
Swarna	3.79	0.30	0	5.12	5.34	2.32
Swarna-Sub1	5.21	2.04	0.77	5.15	5.52	2.07
IR40931	4.25	1.72	0.70	-	-	-
IR49830-7	4.48	2.96	1.93	5.64	5.26	3.54
FR13A	1.95	1.57	1.34	-	-	-
Means	3.85	1.47	0.79	5.22	5.28	2.57
$LSD_{0.05}$ (G)	0.43***	0.49***	0.48***	n.s.	n.s.	0.36***
(E)	0.20***			0.27***		
(GXE)	0.44***			0.45***		

n.s. = not significant; *,**,*** = significant at P<0.05, 0.01, and 0.001, respectively.

During 2007 DS experiments, genotypes were subjected to partial flooding only, to test whether Sub1 lines behave similarly or different compared to their responses following flash-flooding. In this experiment, grain yields of all genotypes were similar under shallow and 30 cm of water depth, but decreased by >50% under severe stress of 50 cm. Partial flooding led to significant differences in panicle number and grain filling (Singh *et al.* 2008). These results showed that stagnant flooding could substantially reduce survival and yield, and is particularly more damaging if it occurs following a period of complete submergence. Varieties with and without Sub1 responded more or less similarly, however, taller genotypes showed much less damage, suggesting that tolerance of these conditions is independent of Sub1. For environments where stagnant flooding is anticipated, Sub1 should be introgressed into relatively taller varieties or varieties capable of partial elongation when incompletely flooded.

COMBINING ADAPTIVE TRAITS FOR RAINFED AND FLOOD-PRONE AREAS

In some of these areas, flooding is seldom the sole cause of low productivity, and in most cases it is compounded with other abiotic stresses, such as drought, nutrient imbalances and various soil problems. This is further complicated by the specific local consumer preferences, particularly the explicit characteristics of plant and grain type and cooking and eating qualities. These complexities are probably behind the fact that conventional breeding has not been very successful in introducing high yielding varieties in these areas, as the case in irrigated ecosystem. Currently only a handful of modern varieties are covering larger areas and still in some areas, local landraces predominate. Opportunities to combine adaptive complex traits had recently become feasible with the progress made in developing molecular tools and information on the use of DNA markers in breeding. These new tools allow genome-based selection even without the necessity to know the genes involved. This approach proves to be effective in enhancing breeding efficiency by eliminating linkage drag and shortening the breeding cycle. Good progress was made at IRRI in fine-mapping relatively large QTLs associated with tolerance to some of the prevalent stresses in rainfed areas, such as salinity, flooding, P and Zn deficiency and more recently, drought. Combining these tolerance QTLs for multiple stresses into high yielding varieties, while retaining their high yield and excellent grain quality of recurrent parents, is now feasible. Varieties that combine tolerance of submergence during germination and vegetative stage together with tolerance to partial long-term stagnant flooding would have a major advantage for achieving higher and stable yields. Molecular markers specific to Sub1 and to QTLs associated with tolerance for anaerobic conditions during germination, and Sub1 + QTLs for salinity tolerance are currently being used to select new lines combining these traits

The tolerance level provided by QTLs currently being targeted for major abiotic stresses common in rainfed areas is mostly below that of the original donor landraces, and efforts should continue to focus on identifying new sources of tolerance through collection and evaluation of native germplasm. Other important QTLs with additive effects should be targeted. Use of MAB to pyramid these QTLs into suitable genetic backgrounds of varieties and breeding lines adaptive to particular rainfed and flood-prone areas will help in accelerating the deployment and adoption of the new varieties and could have enormous impact on enhancing and stabilizing productivity in these areas. The major current limitation to this approach is the relatively large resources needed during the development and use of a MAB system to combine these multiple traits.

MANAGEMENT OPTIONS IN FLOOD-PRONE AREAS

Over the last three decades or so, considerable amount of research was devoted to develop high yielding rice varieties adapted to rainfed and flood-prone areas through both conventional and molecular approaches (HilleRisLambers and Vergara 1982; Mackill *et al.* 1993). However, scant research efforts were devoted to develop crop and nutrient management strategies that can help enhance survival and yield under these conditions. For example, specific nutrient management strategies have not been developed for flood-prone areas and farmers in most cases adopt management practices developed for intensive irrigated systems when resources are available. This is probably because the traditional landraces as well as the available modern high yielding varieties currently available for farmers are less responsive to inputs when subjected to severe abiotic stresses.

In the past few years, the IRRI Consortium for Unfavorable Rice Environments (CURE) developed and tested numerous management options for flood-prone areas, both on station and in farmers' fields (Ella and Ismail 2006; Ram *et al.* 2008). Recommendations are being developed and refined and some of them are being tested and/or out-scaled in target areas. Some of these options are summarized below:

A. **Nursery management:** Nursery management before transplanting can have a big impact on survival and recovery of rice seedlings following submergence. This can increase grain yield by over 40% if complete submergence occurs during vegetative stage. These options should particularly be attractive to farmers since they will be applied on a small area covered by the nursery. The following simple practices should be followed in these areas:

   1. Selecting proper seed bed site: In areas with good soil and good water control. About 200-400 m^2 are probably sufficient for a hectare in the main field.

2. Use low seed rate in the nursery: 50-75 g/m^2 of the nursery, i.e. prepare about 20-30 kg of seeds for each ha of the main field. High seed rates result in thinner and weaker seedlings likely to be damaged by early floods.

3. Thorough land preparation of the nursery. To ensure good seedling establishment.

4. Water management: Do not flood the nursery but keep it saturated throughout, and with good weed and pest management.

5. Proper nutrition: 6 g of N, 4 g of P_2O_5, 2 g of Zn and 1 kg of FYM per m^2 of the nursery area (Equivalent to a rate of 60 kg N, 40 kg P_2O_5, 20 kg Zn and 10 t/ha of FYM), is optimum in areas with low fertility (e.g. in sandy, loamy soil). Do not apply too much nitrogen (less than 3 g N per m^2) if the soil is fertile (Ella and Ismail 2006). Farm Yard Manures are helpful if available and should be combined with inorganic fertilizers.

B. Transplanting:

1. Timing: Use older (about 35-45 days old) seedlings. Transplanting should be done directly after uprooting of the nursery. Make sure the seedling height at transplanting is greater than water depth in the field, sensitivity to submergence is high at this early stage.

2. Plant density and spacing: use 2-3 seedlings per hill. Use closer spacing (15 cm x 15 cm) in the field if high level of standing water is expected, as tillering will be reduced.

C. Post-submergence nutrient management in the main field: If the flood water goes down (field water depth <15 cm) early (15 to 30 days before heading), responses to fertilizer will be good particularly nitrogen. Fertilizers can be applied any time one week after the flood subsides. Use any available information on soil nutrient status or fertilizer responses to decide on which nutrient and how much is needed. Apply about 30-50 kg of N, 20-30 kg of P_2O_5, 20-30 kg of K per ha. If the water level is high in the field, slow release and coated nitrogen sources are preferred if available.

D. Double and triple transplanting: in some flood-prone areas, farmers adopt double or even triple transplanting to produce taller seedlings for transplanting in standing water at the beginning of the season (India and Bangladesh), or to rejuvenate the seedlings while waiting for the flood water to recede to levels that can allow transporting as with the triple transplanting system practiced in Indonesia. This system could be further improved through the choice of proper varieties (e.g. photosensitive varieties seem to be better adapted), or proper management of seedlings in nurseries or upon transplanting in the field (summarized in Ram *et al.* 2008).

These management strategies are developed and tested in combination with tolerant varieties, which is different from foregoing efforts where researchers have been trying to develop strategies using either local landraces or sensitive modern varieties. Landraces are normally not as responsive to inputs because of their limited yield potential and tendency to grow vigorously and lodge when heavily fertilized. The high response observed in tolerant modern varieties under severe stress is probably because they are internally less strained compared with sensitive ones at a particular level of external stress. However, under mild stress conditions, even sensitive modern varieties showed considerable increase in yield in response to certain CNRM practices.

The multifaceted abiotic stresses in rainfed areas (submergence, stagnant flooding, soil problems, drought) and lack of suitable varieties and capital to exploit water resources available during the dry season mean that most of these areas are still mono-cropped with rice during the monsoon season. However, in some countries such as in Vietnam, Bangladesh, India and Thailand, dry season rice became a major crop that transformed farmers' livelihood and resulted in substantial improvements in rice production and food security. This has become possible after investing in irrigation infrastructures as in Vietnam, as well as in the use of subsurface water through shallow tube wells as in Bangladesh. However, this resource is highly unexploited in Indonesia despite the presence of good quality water at shallow depths as in North Sumatra. Dry season rice could provide greater food security because it is less vulnerable to natural hazards, but the system requires initial investment in irrigation and development of suitable short-maturing varieties and proper management options. Community efforts are needed to avoid the damaging effects of rats and birds if just small areas are to be grown during the dry season.

SUMMARY AND OUTLOOK

Flood-prone areas hold enormous potential for future food production and security. This is because these areas are highly underexploited and the yield gap is particularly large compared to more favorable areas notwithstanding their enormous resources of good quality water and land. Solutions to existing problems are now becoming more feasible and good progress already made in germplasm improvement and management options, and with dramatic impact demonstrated in farmers' fields. The success of Sub1 introgression lines, impact of nursery management, seedling handling and post-submergence nutrient management are a few examples. Future efforts should focus on combining multiple tolerances of major abiotic stresses prevailing in these areas as flooding during germination and vegetative stage and long term partial flooding, tolerance of delayed planting, alternatives and/or proper options for double and triple transplanting, and proper germplasm and practices to further intensify and diversify production during the more secure dry season. New strategies are also needed to bridge the knowledge gap between researchers and farmers regarding the needs and progress made in the development of new rice varieties and technologies. Available technologies should reach their target users through more effective and efficient participatory and adaptive research and extension networks. High quality seeds of the newly developed high yielding varieties should be made available to farmers through large scale seed production involving farmers' communities, the private sector, NGOs and government agencies. Emphasis should also be made on extending proper management packages in association with the new varieties to ensure their desired performance.

REFERENCES

Angaji S.A., Septiningsih E., Mackill D.J. and Ismail A.M. 2008. Identification of QTLs associated with tolerance to anaerobic conditions during germination in rice (*Oryza sativa* L.). (Submitted).

Das K.K., Sarkar R.K. and Ismail A.M. 2005. Elongation ability and non-structural carbohydrate levels in relation to submergence tolerance in rice. Plant Sci. 168: 131-136.

Ella E.S. and Ismail A.M. 2006. Seedling nutrient status before submergence affects survival after submergence in rice. Crop Sci. 46: 1673-1681.

Ella E., Kawano N., Yamauchi Y., Tanaka K. and Ismail A.M. 2003. Blocking ethylene perception enhances flooding tolerance in rice seedlings. Functional Plant Biology. 30: 813-819.

HilleRisLambers D. and Vergara B.S. 1982. Summary results of an International collaboration on screening methods for flood tolerance. *In*: Proceedings of the 1981 International Deepwater Rice Workshop. Los Banos (Philippines): International Rice Research Institute. p. 347-353.

Ismail A.M., Ella E.S., Vergara G.V. and Mackill D.J. 2008. Mechanisms associated with tolerance of flooding during germination and early seedling growth in rice (*Oryza sativa* L.). (Submitted).

Ismail A.M., Thomson M.J., Vergara G.V., Rahman M.A., Singh R.K., Gregorio G.B., and Mackill D.J. 2008. Designing resilient rice varieties for costal deltas using modern breeding tools. *In*: C.T. Hoanh, B. Szuster, S.P. Kam, A. Noble, A.M. Ismail (eds.); Tropical Deltas and Coastal Zones Community, Environment and Food Production at the Land-Water Interface. CABI Publishing (In press).

Jackson M.B. and Ram P.C. 2003. Physiological and molecular basis of susceptibility and tolerance of rice plants to complete submergence. Ann. Bot. 91: 227-241.

Mackill D.J., Amante M.M., Vergara B.S. and Sarkarung S. 1993. Improved semi-dwarf rice lines with tolerance to submergence of seedlings. Crop Sci. 33: 749-753.

Neeraja C., Maghirang-Rodriguez R., Pamplona A., Heuer S., Collard B., Septiningsih E., Vergara G., Sanchez D., Xu K., Ismail A. and Mackill D. 2007. A marker-assisted backcross approach for developing submergence-tolerant rice cultivars. Theoretical and Applied Genetics. 115: 767-776.

Ram P.C., Mazid M.A., Ismail A. M., Singh P.N., Singh V.N., Haque M.A., Singh U., Ella E.S. and Singh B.B. 2008. Crop and resource management in flood prone areas: farmer's strategies and research developments. *In*: Natural Resource Management for poverty reduction and environmental sustainability in fragile rice-based systems. Workshop Proceedings. March 8-9, 2006, Dhaka, Bangladesh. International Rice Research Institute, Philippines. (In press).

Ram P., Singh B., Singh A., Ram P., Singh P, Singh H., Boamfa I, Harren Santosa F., Jackson M, Setter T., Reuss J., Wade L., Singh V., and Singh R. 2002. Submergence tolerance in rainfed lowland rice: physiological basis and prospects for cultivar improvement through marker-aided breeding. Field Crops Research. p. 131-152.

Sarkar R.K., Reddy, J.N., Sharma, S.G. and Ismail, A.M. 2006. Physiological basis of submergence tolerance in rice and implications for crop improvement. Current Sci. 91: 899-906.

Septiningsih E.M., Pamplona A.M., Sanchez D.L., Neeraja C.N., Vergara G.V., Heuer S., Ismail A.M. and Mackill D.J. 2008. Development of submergence-tolerant rice cultivars: the Sub1 locus and beyond. Annals of Botany. (In press).

Singh S., Vergara G., Sharma H.P., Mackill D.J. and Ismail A.M. 2008. Prolonged partial stagnant flooding and its effect on rice genotypes contrasting in submergence tolerance. Abstract booklet of the 5th International Crop Science Congress. April 14-18, 2008. Jeju, Korea.

Singh S., Vergara G., Sharma H.P., Pamplona A., Mackill D.J., and Ismail A.M. 2007. Field performance of Sub1 under normal and flooded conditions. Abstract booklet of 9th Conference of the International Society for Plant Anaerobiosis, 18th - 23rd November, 2007, Matsushima, Sendai, Japan.

Swain D.K., Herath S., Pathirana A., Mittra B.N. 2005. Rainfed lowland and flood-prone rice: A critical review on ecology and management technology for improving the productivity in Asia. In: Herath S., Dutta D., Weesakul U., Gupta A.D. (eds). Proceeding of the International Symposium on Role of Water Sciences in Transboundary River Basin Management. Thailand, 2005. p. 201-211.

Xu K., Xu X., Fukao T., Canlas P., Maghirang-Rodriguez R., Heuer S., Ismail A.M., Bailey-Serres J., Ronald R.C., Mackill D.J. 2006. Sub1A is an ethylene-response-factor-like gene that confers submergence tolerance to rice. Nature. 442: 705-708.

Xu K. and Mackill D.J. 1996. A major locus for submergence tolerance mapped on rice chromosome 9. Mol Breeding. 2: 219-224.

Yamauchi M., Winn T. 1996. Rice seed vigor and seedling establishment in anaerobic soil. Crop Sci. 36: 680-686.