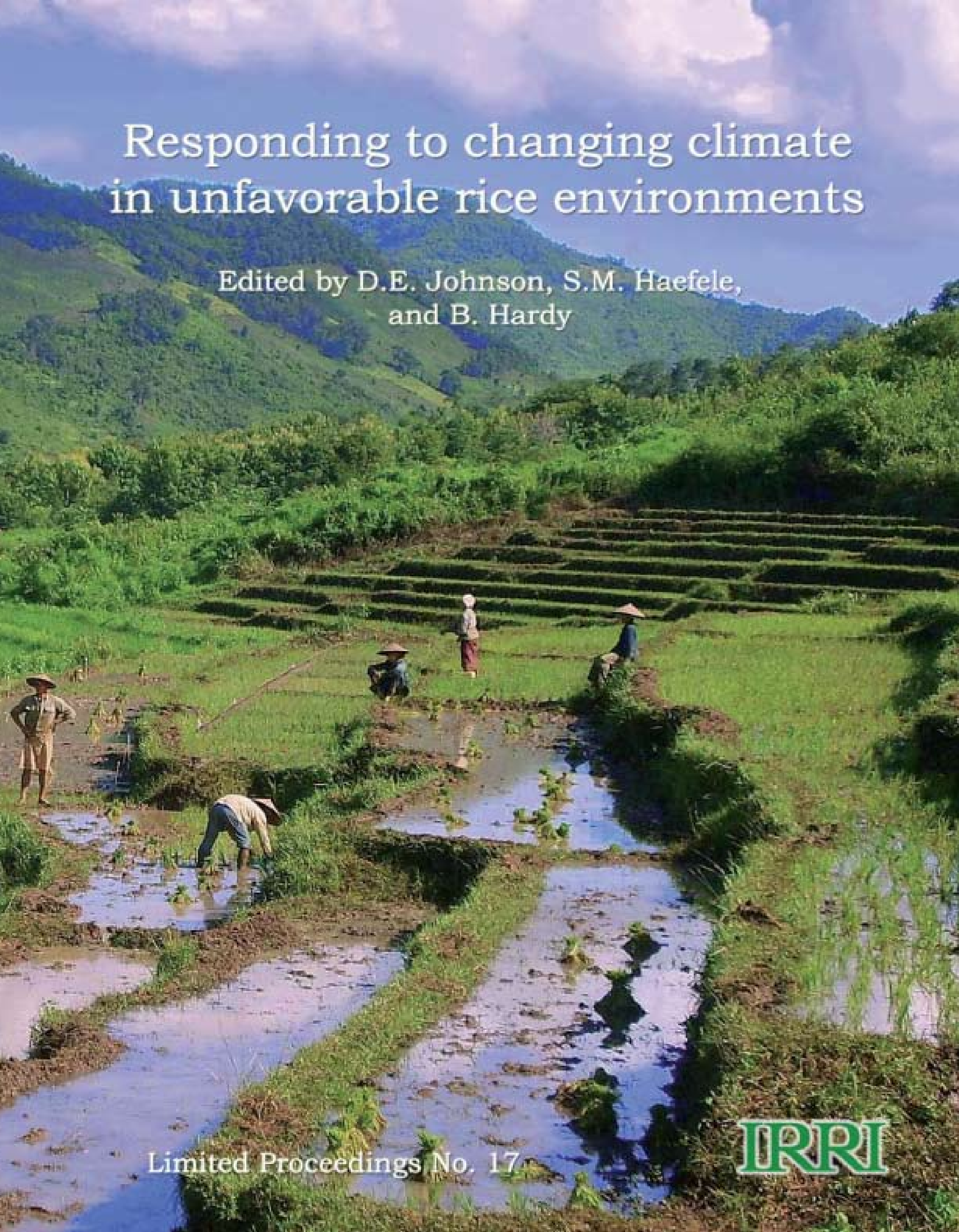
Responding to changing climate in unfavorable rice environments

Edited by D.E. Johnson, S.M. Haefele, and B. Hardy



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Responding to changing climate in unfavorable rice environments

4 May 2010,
Siem Reap, Cambodia

D.E. Johnson, S.M. Haefele, and B. Hardy, editors

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Foreword

Rice is the most important food crop of the developing world and the staple food of more than half of the world's population, many of whom are also extremely vulnerable to high rice prices. Worldwide, more than 3.5 billion people depend on rice for more than 20% of their daily calories. The phrase "rice is life" is not to be taken lightly since rice is deeply embedded in social practices and customs across Asia. Thus, any rice shortages affect society beyond the extent that price, caloric intake, yield growth rates, and international trade may suggest. Significant disruptions of rice supplies will have far-reaching social and political ramifications.

Global climate change has potentially grave consequences for rice production and, consequently, global food security. Land-use systems in many rice-producing countries are highly vulnerable to climate change and have little capacity to cope with its impacts. Conditions for rice farming will deteriorate in many areas, through changing rainfall patterns, thermal stress, sea-level rise, floods, and more intense tropical cyclones. Almost half the rice area is in the rainfed uplands and lowlands, and therefore vulnerable to drought that may occur with changing rainfall patterns. Likewise, the incidence of flooding may increase in some areas. It is disconcerting that more than half of the growth in Asian rice production over the past decades came from the "delta countries," such as Vietnam and Bangladesh—precisely those countries most vulnerable to sea-level rise and climatic extremes. What will be the sustainable rice-based cropping systems and crop management practices of the future?

In a "convenient convergence," researchers within the Consortium for Unfavorable Rice Environments (CURE) have been working to overcome drought, salinity, and submergence in rice—major problems that are likely to get worse in future climates. In Cambodia, in May 2010, CURE held a workshop on Responding to changing climate in the unfavorable rice environments. The aim was to review progress with the development of tolerant varieties and crop management options to reduce farmers' risk and improve the resilience of farm households. Researchers and extension staff representing 28 institutions from 10 countries attended.

This publication includes a selection of papers describing the expected changes in climate, efforts in India and Bangladesh to tackle the likely impact of the changes, the development of varieties to counteract the major stresses, advances in crop management to improve returns and increase options available to farmers, and the likely economic impact of climate change. This publication is intended to provide an overview of the likely threats, current opportunities for adaptation, and some of the likely implications. I believe this will be a useful resource for researchers, extension staff, and policymakers as they seek solutions to the problems posed by changing climates and one of the major concerns of our time.

Robert S. Zeigler
Director General

About CURE

The Consortium for Unfavorable Rice Environments (CURE) is a regional platform for partnerships among institutions led by national agricultural research and extension systems (NARES) from South and Southeast Asia. It focuses on rice farming systems where low and unstable yields are commonplace and where extensive poverty and food insecurity prevail.

CURE aims to benefit the 100 million farm households in Asia that are dependent on rice. Working on rice environments with problem soils that rely on unpredictable rains and that are susceptible to flooding, farmers had no recourse but to continue to grow mainly traditional varieties and use very few, if any, external inputs. Consequently, productivity gains have been small. To improve the livelihoods of millions of farmers in these unfavorable rice environments, an innovative approach is needed to address the challenges of achieving sustainability and raising productivity.

CURE's strategy involves on-site farmer participatory research linking scientists from NARES, international research centers, and advanced research institutions using a multidisciplinary approach for technology generation, validation, and dissemination. CURE also closely collaborates with local government units and nongovernment organizations to disseminate technologies over a wider area. Membership comprises 26 institutions in 10 countries: Bangladesh, Cambodia, India, Indonesia, Lao PDR, Myanmar, Nepal, the Philippines, Thailand, and Vietnam.

Through improved rice productivity, households can diversify into income-generating activities and thereby achieve a higher standard of living and a better quality of life.

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http://irri.org/cure
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Introduction

Total rice production in Asia has more than doubled over the past 50 years; however, drought and floods remain the main sources of risk and uncertainty for farmers. It is estimated that in Asia some 23 million ha of rice are affected by drought. Most of these areas are rainfed,[1] although water supply is also insufficient in some irrigated areas. Further, some 16 million ha, mainly on the floodplains of the major rivers, are affected by flood and 11 million ha are affected by salinity in coastal and inland areas. Substantial areas are also affected by more than one of these stresses although at different crop stages or seasons. In the future, drought, salinity, and submergence are expected to occur more frequently as sea levels rise, rainfall patterns change, and the incidence of dramatic climate events, such as typhoons, increases. The environments that are already considered unfavorable rice-growing areas are therefore in many cases likely to become less favorable still.

Prior to considering measures to enable the adaptation to climate change, it is worth reflecting on the characteristics of the unfavorable rice environments and the rice farmers who live there. These are areas where drought, submergence, problem soils, and other abiotic stresses pose major constraints to rice production, and these environments tend to predominate in the "poverty hot-spots" in Asia.[2] Rice is often the main source of staple food, employment, and income for rural populations. Grain yields remain low at 1.0 to 2.5 t ha^{-1}, and the 100 million farmers who depend on these crops often lack the capacity to acquire food, even at lower prices, because of low productivity in food production and limited employment opportunities elsewhere. The small size of farms, poverty, insecure tenure, and high risks in the unfavorable rice environments make farmers unwilling to invest in improved rice production and resource management options, thus preventing farmers from benefiting in good seasons. Reducing the risk to farmers through varietal and crop management options can therefore have multiple impact on the people's livelihoods in these areas.

The development and transfer of improved farm-level resource management strategies require a good understanding of the interactions of soil, water, and pests, and the integration of knowledge into the development of improved crop management options. The high variability in these environments and the need to take account of farmers' aspirations require the evaluation and refinement of options with farmer participatory research. Women are often more strongly committed than men to rice farming in unfavorable areas. Women farmers therefore need to be involved in the conduct of participatory research that evaluates crop varieties and management options in order to increase the chance that the resulting technologies are appropriate and will be more widely adopted.

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[1] Pandey S, Bhandari H. 2010. Introduction. In: Pandey S, Bhandari H, Hardy B, editors. Economic costs of drought and rice farmers' coping mechanisms: a cross-country analysis. Los Baños (Philippines): International Rice Research Institute. p 1-8.
[2] IRRI. 2007. Bringing hope and improving lives.

Improving farmers' flexibility in deciding on crop, timing, and establishment options is an important feature in technology design for the drought-prone areas.[3] Improving farmers' flexibility through different climate-response options provides alternatives. Aside from reducing the chance of low income, access to different climate-response options gives farmers the chance to avail of opportunities to improve their income when favorable conditions occur. Such adaptive systems are already practiced by farmers in rainfed systems, such as in eastern India, where farmers switch between dry seeding of a traditional variety and transplanting of modern varieties if the rains arrive early.[4] It is likely that, in the flood-prone and saline-prone environments, greater flexibility in the systems would also be beneficial to farmers as this would allow them to adapt to the prevailing conditions to avoid situations that will probably depress incomes and have opportunities to gain additional revenue.

Over the last three decades, sources of greater tolerance of stresses have been discovered in cultivated and wild rice germplasm, making genetic enhancement a valuable means for reducing risks and improving the livelihoods of the rural poor. CURE coordinates strategic research collaboration between IRRI and national systems on the participatory development and testing of technologies in rainfed environments in partnership with farmers, and it promotes resource sharing and information exchange across national programs.

As Dr. Robert Zeigler describes in the Foreword, a "convenient convergence" lies in the fact that research undertaken for the unfavorable rice areas and aimed at drought, submergence, and salinity, in particular, provides advances and insights that will serve to meet the challenges of climate change. At the mini-symposium held in Seam Reap, Cambodia, titled "Responding to changing climate in the unfavorable rice environments" on 3-5 May 2010, the research directions and progress made in reducing risks for rice producers in the unfavorable rice environments were presented and discussed. This was part of a program of activities to raise awareness on some of the developments intended to counteract the expected constraints that future climate might bring.

In this publication, different aspects of research and development are presented that are relevant not only to improving the livelihoods and reducing poverty in the unfavorable rice areas, but also options to help farmers to adapt to the likely threats of future climates. The chapters cover (1) the importance of rice to the rural poor and the threat of climate change, (2) a review of some of the expected changes in climate, (3) likely impacts and initiatives at the national level in India, (4) developments in rice varietal tolerance of stress, and (5) crop and natural resource management strategies to reduce risk and raise productivity.

We hope that the ideas and concepts presented here will provide the basis for discussions and future activities that will improve the livelihoods of rice farmers in the unfavorable rice environments.

D.E. Johnson
CURE Coordinator

[3] Pandey S, Bhandari H. 2010. Summary and recommendation. In: Pandey S, Bhandari H, Hardy B, editors. Economic costs of drought and rice farmers' coping mechanisms: a cross-country analysis. Los Baños (Philippines): International Rice Research Institute. p 185-203.

[4] Fujisaka S, Moody K, Ingram K. 1993. A descriptive study of the farming practices for dry-seeded rainfed lowland rice in India, Indonesia and Myanmar. Agric. Ecosyst. Environ. 45:115-128.

Rainfed rice, farmers' livelihoods, and climate change

Sushil Pandey, Huaiyu Wang, and Humnath Bhandari

Rice is grown worldwide on about 158 million hectares, with a total output of 456 million tons of milled rice. It accounts for 20% of the total calorie intake globally. It is a staple crop of Asia and is consumed by more than 3 billion Asians on an almost daily basis. Given its importance, an adequate and stable supply of rice is fundamental to economic growth, food security, and poverty reduction in Asia.

The likely consequences for rice production of long-term climate change resulting from global warming are a major concern, given the strategic importance of rice. The temperature and rainfall changes that will accompany climate change will require suitable adaptations. The nature and type of adaptation required may vary across geographical locations and among farmers. Suitable adaptation strategies need to be developed to help farmers to minimize any adverse effects on rice production.

The objective in this chapter is to provide some perspectives on the likely consequences of climate change for rainfed rice farming and farmers' livelihoods. It is organized as follows. The relationship between rainfed rice and poverty is discussed first. This is followed by some analysis of the effects of abiotic stresses on rice production losses in rainfed environments and the farm-level consequences of such losses. A discussion of how climate change will likely increase farmers' vulnerability is subsequently provided. Some thoughts on possible strategies to reduce vulnerability and improve farmers' adaptation to climate change conclude.

Rainfed rice and poverty

Rainfed rice area in Asia is around 55 million ha (or 40% of the total rice area in Asia). It accounts for 26% of the total rice production of Asia and provides food for around 1.3 billion people. Around 80 million farm households are engaged in growing rice in rainfed conditions. Rainfed rice is also very important in sub-Saharan Africa (SSA), where 84% of the total rice area of 9 million ha is rainfed. Overall, rainfed rice is very important as the food security and livelihoods of millions of farmers and consumers depend on it.

In Asia, countries with a large proportion of rainfed rice area are India, Thailand, Bangladesh, Myanmar, Indonesia, and Cambodia (Table 1). India accounts for a third of the total rainfed rice area in Asia, with rainfed rice being concentrated mainly in its eastern region. Rice yields in these rainfed environments are low and variable. High risks in these environments mean that risk-averse small farmers invest less in yield-enhancing inputs such as fertilizer.

The overall incidence of poverty is also very high in rainfed environments. State-level data for India indicate a positive correlation between the proportion of rainfed area and the

Table 1. Importance of rainfed rice in Asia, 2006-08.

Country	Rice area (000 ha)	Rainfed rice area (000 ha)	National rice yield (t/ha)
Bangladesh	11,224	5,051	3.97
Cambodia	2,565	2,360	2.62
India	43,823	20,159	3.27
Indonesia	11,952	5,498	4.79
Laos	774	666	3.48
Myanmar	7,867	5,507	3.69
Nepal	1,513	772	2.69
Philippines	4,298	1,418	3.75
Thailand	10,330	7,954	2.96
Vietnam	7,315	3,292	5.03
Others	38,106	2,827	3.65
Total	139,768	55,503	–

Data source: IRRI World Rice Statistics and IRRI Strategic Plan, 2007-2015.

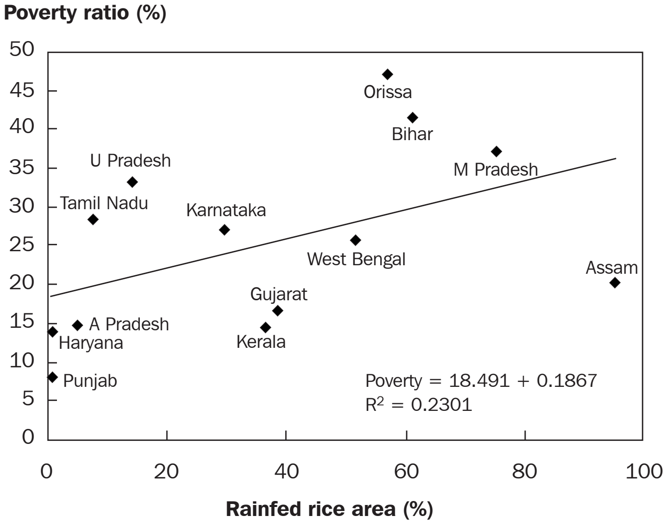
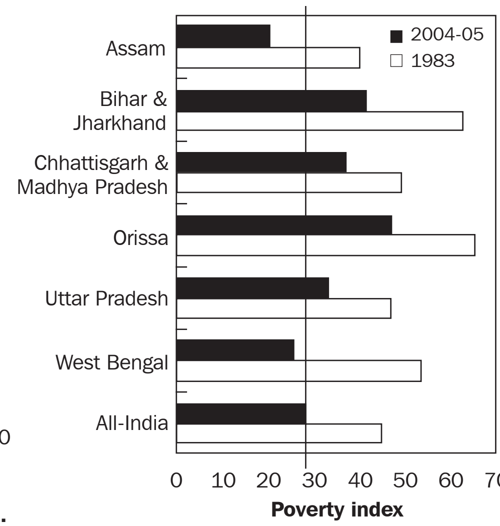


Fig. 1. Association of poverty and rainfed rice area at Indian sites.



No. of poor people in rural area (million)	
Assam	4
Bihar & Jharkhand	35
Chhattisgarh & Madhya Pradesh	20
Orissa	13
Uttar Pradesh	36
West Bengal	15
All-India	170
Eastern India	122

Fig. 2. Incidence of poverty in eastern India.

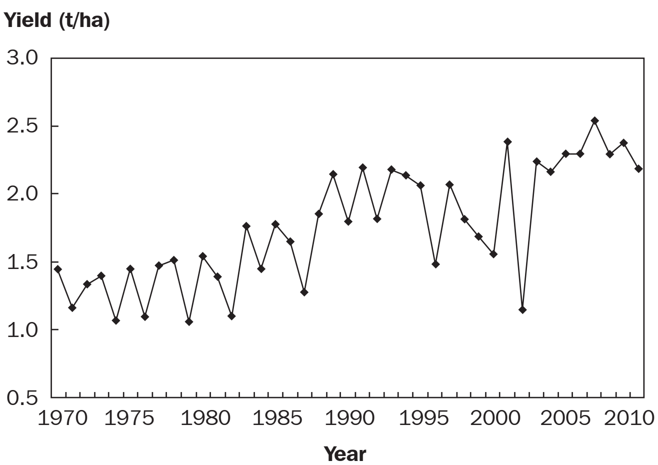


Fig. 3. Trends in rice yield in Orissa, 1970-2010.

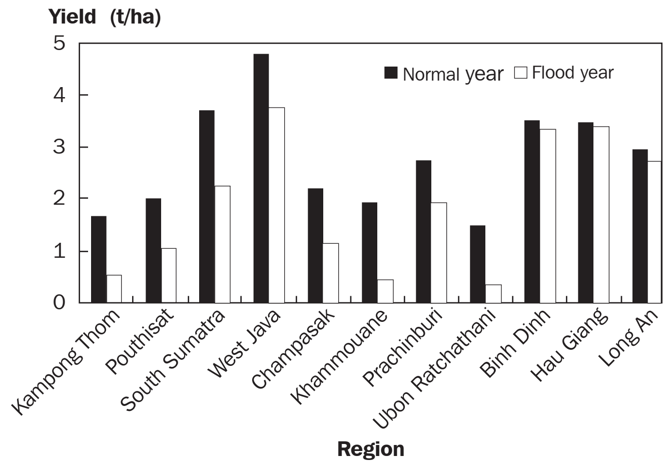


Fig. 4. Impact of flooding on yield, wet season.

incidence of poverty (Fig. 1). Most of the states of eastern India have poverty incidence higher than the national average, with the total number of poor rural people in eastern India accounting for two-thirds of the total rural poor in India (Fig. 2).

Abiotic stresses, production losses, and farm-level consequences

The major abiotic stresses that affect rice yield and production in rainfed areas are drought and submergence. The yield trend in the Indian state of Orissa, where rice is mainly grown under rainfed conditions, clearly illustrates a high temporal variability in rice yield caused mainly by drought (Fig. 3). Drought occurs about once in three years. The value of rice production lost in drought years has been estimated to be as high as 36% of the value of rice production in eastern India (Table 2). Considering both drought and nondrought years, this is equivalent to an average annual production loss of about 7% at the aggregate level.

The aggregate loss estimate above masks the severity of effects that often occur at the farm level (Table 3). A very large proportion of the rice area and rice-growing households is affected by abiotic stresses in eastern India, with yield loss in affected years being higher than 42% in most cases. In Southeast Asia, the effect of flooding on rice yield is also very high (Fig. 4). This translates into household income losses of 25–50%, with the loss in rice income accounting for the lion's share of the household income loss (Table 4).

Although farmers deploy various strategies to cope with these income losses, the ultimate consequence to poor farmers is a reduction in their food consumption. Empirical estimates indicate that poorer groups have no choice but to reduce their consumption by as much as 15–20% (Pandey et al 2007). The welfare consequences of such reductions in consumption are quite severe as poor people have low consumption even in normal years without drought/submergence. The long-term economic and social consequences can also be severe, especially when drought occurs in consecutive years (Pandey et al 2007). The income losses (some annual while others persist over several

Table 2. Estimated value of crop production loss due to drought.

Country	Drought years			Annual	
	Quantity of rice production loss (million tons)	Value of crop production loss (million US$)	Ratio of loss to average value of production (%)	Value of crop production loss (million US$)	Ratio of loss to average value of production (%)
Southern China	1.2	133	3	16	0.4
Eastern India	5.4	856	36	162	6.8
Northeast Thailand	0.7	85	10	10	1.2

Source: Pandey et al (2007).

Table 3. Incidence and effects of drought and submergence.

Item	Submergence				Drought	Salinity
	Nadia	Jamalpur	Kurigram	Habiganj	Rajshahi	Satkhira
Rice area affected by stress (%)	0.6	>75	0.55	0.75	0.75	0.6
Households affected by stress (%)	0.5	>90	40–45	0.5	80–100	0.6
Yield losses (%)	0.46	0.72	0.47	0.51	0.19	–

Source: STRASA focus group discussions (2008).

Table 4. Income losses during flood years.

Country	Loss in total income (%)	Contribution of rice to total income loss (%)
Cambodia	56	54
Indonesia	25	68
Lao PDR	27	96
Thailand (Prachinburi)	24	83
Thailand (Ubon Ratchathani)	51	18
Vietnam (Long An)	28	92

Source: IRRI-Submergence Project farm household survey, 2008.

years) directly result in incidence of poverty. Many of those people tend to fall even deeper into poverty, making it much harder for them to escape it.

Climate change and farmers' vulnerability

It is now well established that global warming and the resulting climate change will affect agriculture in several ways. In the context of rice production, the three main factors that will reduce rice production are

- Increases in temperature
- Increased rainfall variability
- Sea-level rise

An increase in average temperature, and especially nighttime temperature, has been shown to reduce spikelet fertility and cause an overall reduction in the yield of rice (Peng et al 2004, Sumfleth and Haefele, this volume). Predictions based on climate modeling indicate that extreme rainfall events will be more frequent, leading to higher incidence and greater intensity of drought and submergence in rice-growing areas. The expected increases in the frequency of flooding and sea-level rise are similarly likely to reduce rice production from the traditional "rice bowls" of the Asian river deltas. In Asia, modeling results indicate that rice production may decrease by as much as 14% by 2050 relative to the baseline scenario of no climate change (Wassmann et al 2010). In addition, increased climatic variation will most certainly translate into increased production variability at the aggregate level, also causing wider fluctuations in rice production and prices.

The above scenario pertains to the total likely effects of climate change considering all rice-growing areas. In rainfed rice farming, households with fewer economically active members in the family, smaller farm size, and a larger proportion of area under drought- or submergence-prone fields, less education, limited income diversification, and a smaller asset base tend to be more vulnerable to climatic risks (Bhandari et al 2007). Such households are also often the poorest. The poverty consequences of climate change for poor rice farmers can indeed be quite severe.

Technology options

Providing multiple and more flexible technological options is an important strategy to reduce household vulnerability. The availability of technological options and the nature of the production environment largely determine household vulnerability to climate change. Households are most vulnerable if

Technology options		Production environment: Less favorable	Production environment: More favorable
	More	• Moderate flexibility • Low to moderate vulnerability	• High flexibility • Low vulnerability
	Fewer	• Low flexibility • High vulnerability	Low to moderate flexibility

Fig. 5. Technology options and vulnerability.

the production environment they operate in is less favorable and the technological options are also limited (lower left quadrant in Fig. 5). In such situations, the incidence of poverty and food insecurity tends to be high also. The provision of additional technological options will help reduce their vulnerability and improve welfare (movement to upper left quadrant in Fig. 5). For unfavorable rainfed environments, this means that rice technologies that have stress tolerance would be important for improving adaptation to climate change. Other complementary options through the provision of insurance, the provision of safety nets, and longer-term investment in promoting income diversification will also be beneficial. Of course, vulnerability can be reduced by converting less favorable environments to more favorable environments (horizontal movement toward right-side quadrants in Fig. 5), but such changes tend to be expensive and of a long-term nature.

Concluding remarks

In concluding, both technological and policy interventions are needed to develop a more resilient livelihood system suited to poor rainfed rice farmers. In addition to improved rice varieties that are tolerant of various abiotic stresses, rice technologies that improve the flexibility of farming operations to continually adapt to seasonal production conditions are needed. Similarly, diversification of income is an important risk-coping strategy and rice technologies that facilitate diversification of farming activities will improve adaptation to climate change. On the policy side, improvements in rural infrastructure and marketing are needed to promote diversification of rural income. Widening and deepening the rural financial market will also be a critical factor in reducing fluctuations in production and consumption. This, combined with newer approaches to agricultural insurance and productive safety nets, could complement technological innovations to improve poor farmers' adaptation to climate change.

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Notes

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Climate change and unfavorable rice environments: overview of approaches to assess trends and future projections

Kay Sumfleth and Stephan M. Haefele

The likely impacts of climate change on rice-based agroecosystems in Asia are uncertain, especially for rainfed rice systems in the unfavorable environments that are vulnerable to precipitation changes. Regional impacts of climate change are typically assessed quantitatively through spatially downscaling a global circulation model (GCM), but this approach is inherently biased through the GCM selected, which is typically not more than one. In this paper, we pursue a different approach that is based on an ensemble analysis of several GCMs. In the first section, the ensemble analysis is illustrated by using two rainfed rice environments (in eastern India and Bangladesh) as examples. Although the different GCMs showed a similar overall trend of declining precipitation, major discrepancies have occurred in seasonal aspects of climate change. The spatial downscaling of predicted changes in precipitation projected that the changes are varying throughout the months and regions, probably further increasing the severity and the areas already plagued by floods and droughts. The second section of the paper assesses the potential and constraints of seasonal forecasting as a means to alleviate losses in rice production. Drought is a major production constraint in rainfed rice, so that forecasts on drought occurrence can be used to alleviate losses. In a broader sense, short-term and long-term climate projections could be a key for achieving rising productivity in unfavorable rice environments.

Climate change is arguably the most significant global environmental threat of the 21st century (IPCC 2001). Climate change will have many consequences, including changes in temperature and precipitation regimes, increased year-to-year variability, as well as greater occurrence of extreme events. However, uncertainty is still high with respect to regional differences in the speed and extent of changing patterns of rainfall and temperature extremes or droughts. The impacts on rice-based agroecosystems are even more uncertain, especially in unfavorable rice environments highly exposed to direct and indirect consequences of climate change. In the regional context of Asia, unfavorable rice environments encompass large swaths of drought- and submergence-prone areas as well as salinity-affected areas in the delta regions.

The regional impacts of climate change are typically assessed quantitatively through spatially downscaled global circulation models (GCMs) that are coupled with crop or hydrological/hydrodynamic models (Salathé 2005). This modeling approach is characterized by considerable uncertainties. Model comparisons conducted by the Intergovernmental Panel on Climate Change (IPCC) clearly revealed disagreement between various GCMs and regional climate change impact assessments, so that reliance on a single GCM is inappropriate for a reliable projection of climatic trends (IPCC 2007). Moreover, this downscaled information on regional climate impacts is largely missing for rice-producing countries in Asia (Ashfaq et al 2009), whereas detailed information concerning long-term projections in terms of temperature as well as precipitation patterns, monsoon onsets, and associated uncertainties would be crucial for adaptation strategies.

A global climate or circulation model is a complex simulation model that uses mathematical (differential) equations to represent the physical laws governing the interrelated behavior of the atmosphere, oceans, sea-ice, and land surface, and the interconnected physical processes that determine weather and climate on a global scale. It simulates these processes on a grid that divides the atmosphere, ocean layers, and soil layers into more than a million three-dimensional boxes, globally. Recent simulation studies of global climate models show reliable conformity with measured mean temperature anomalies over the past 150 years. The global climate models also simulate changes in greenhouse gas and aerosol content of the atmosphere with good agreement of observed data under consideration of anthropogenic and natural forcing. The output of these global models is a presentation of daily as well as hourly weather patterns, and the development of temperate and tropical weather structures over time, respectively. As for the resolution of GCMs, one grid cell covers between 150 km × 150 km and 300 km × 300 km of Earth's surface. The long-term average of daily weather patterns is simulated with plausibility by running the model for very long periods of time (approximately 10,000 years), simulating the slow changes of past climate and then projecting them decades

Table 1. Benchmark sites for irrigated (IR) and rainfed (RF) rice crops.

Benchmark site	First rice crop	Second rice crop
Cuttack, eastern India (20º16´N, 85º31´E)	RF (May to Oct.)	RF (Dec. to May)
Rangpur, northwest Bangladesh (25º45´N, 89º15´E)	RF (June to Nov.)	IR (Feb. to June)

or even centuries into the future. At present, 25 GCMs and 12 climate change scenarios are freely available and published by the IPCC (see Table 1). These *climate change scenarios* encompass reasonable assumptions of anticipated emissions resulting from individual or organizational behavior. They have been grouped by the IPCC in so-called SRES (Special Report on Emissions Scenarios) emission families according to the fourth Assessment Report published by the IPCC. At the top end of the scenarios (mean increase of 5.8 °C), extreme growth in CO_2 emissions is assumed, combined with very high sensitivity of climate to greenhouse gases, more than what is consistent with the observed 20th-century warming. Likewise, scenarios at the low end (mean increase of 1.8 °C) are probably unrealistic without significant policy efforts (IPCC 2007).

Analyzing global multimodel data sets or ensemble data of projected patterns of precipitation and temperature changes shows clearly that an increase in the amount of precipitation is very likely in high latitudes, while decreases are likely in most subtropical land regions, continuing observed patterns in recent trends. For regional agricultural impact assessments as well as hydrological impact assessments, the resolution of GCMs, however, is insufficient. Practical approaches such as empirical statistical downscaling, stochastic weather generators, and particularly dynamic regional climate models can be basically applied to increase the spatial resolution of GCMs. Regional climate models (RCM) such as PRECIS—applied by the International Rice Research Institute (IRRI)—can deliver high-resolution agro-meteorological data with horizontal resolutions of up to 25 km on a daily basis. On the other hand, simpler approaches such as empirical statistical downscaling are available. These methods use environmental correlations to disaggregate large climate variations into small-scale climate patterns.

This paper attempts to give a brief overview of different approaches to assess climate change, including their uncertainties. The paper has two parts, the presentations of (1) a GCM "ensemble analysis" through two case studies of rainfed rice environments and (2) seasonal forecasting as a tool for forecasting extreme climate events such as drought. Additionally, we discuss some impacts of major climate change stresses, namely, drought, on crop production and show adaptation options as well as options for raising productivity for unfavorable rice environments under a changing climate.

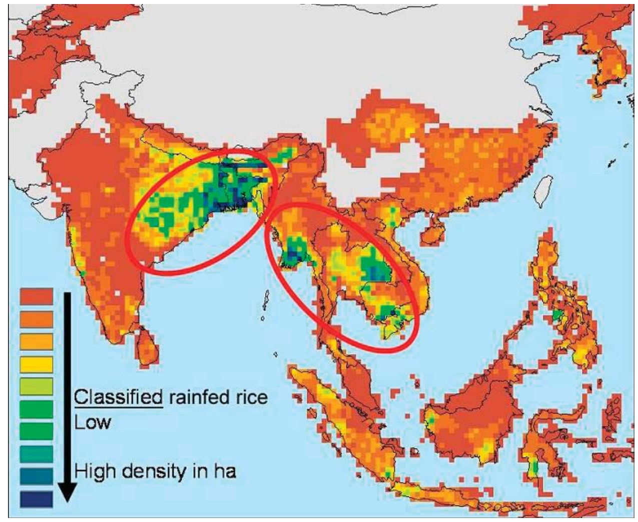

Fig. 1. Spatial distribution of rainfed rice areas in South, Southeast, and East Asia on the basis of FAO and IIASA's Global Agroecological Zone Assessment (for a more detailed description, see Monfreda et al 2008).

GCM ensemble analysis for assessing long-term trends

Materials and methods

Figure 1 shows the distribution of rainfed rice agriculture in South, Southeast, and East Asia (Monfreda et al 2008) and two benchmark sites with irrigated (IR) and rainfed (RF) rice crops are listed in Table 1. A projection of future climate, climate change, and its impact on unfavorable rice environments was conducted by using ensemble models, including all the global climate models listed in Table 2.

The main focus for this paper is the analysis of two rainfed rice production sites (see Table 1) with different raw GCM outputs of the 1% to 2x scenario. This scenario reflects a transient climate response to a 1% per year increase in CO_2 concentration of the atmosphere. The CO_2 concentration increases (starting from 348 ppmv) with a 1% per year compound rate

Table 2. General circulation models (GCM) used and their main characteristics.

Acronym	Name	Source	Resolution
BCCR-BCM 2.0	Bergen Climate Model	Nansen Environmental and Remote Sensing Center, Norway	1.9º × 1.9º
CGCM3.1 (T47)	Coupled Global Climate Model	Canadian Centre for Climate Modeling and Analysis, Canada	~3.75º × 3.75º
CSIRO-Mk 3.5	CSIRO Mark 3.0	CSIRO Division of Marine and Atmospheric Research, Australia	~1.9º × 1.9º

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Table 2 **continued from page 6.**

Acronym	Name	Source	Resolution
ECHAM5/ MPI-OM	European Centre for Medium-Range Weather Forecasts, Hamburg	Max-Planck Institute, Germany	~1.88° × 1.88°
GFDL-CM2.0	Geophysical Fluid Dynamics Laboratory – Climate Model	Geophysical Fluid Dynamics Laboratory, USA	2.0° × 2.5°
MIROC3.2 (hires)	Model for Interdisciplinary Research on Climate	Center for Climate System Research, Japan	~1.1° × 1.1°
UKMO-HadGEM1	Hadley Centre Global Environmental Model	Hadley Centre for Climate Prediction and Research, UK	~1.25° × 1.87°

Source: IPPC Data Distribution Center.

until it reaches twice that value (696 ppmv) in the 70th year, and remains fixed at this plateau thereafter.

We compiled region-specific records from major GCMs (see Table 2). For the baseline comparison—the juxtaposition of observed and simulated climate data in the period of 1960 to 2000—we used CRU data. CRU data (Climate Research Data, www.cru.uea.ac.uk/) with time series of month-by-month variations from 1960 to 2000 are high-resolution climate grids that can be taken as a reference for modeling studies. The displayed time frame of this GCM analysis is 2011-30 and 2031-50. Although all climate models are calibrated with long time series and declared as valid, we show only the synthesized results of this analysis.

We used the ensemble forecast approach because it seems the best method to reflect the uncertainty ingrained in different climate scenarios as well as seasonal or short-term weather forecasts. Figure 2 shows an ensemble of 20 weather forecasts provided by the National Center for Atmospheric Research (NCAR) for South and Southeast Asia and for a time period of 16 days. The resulting maps (Fig. 2) are preliminary estimates and it should be taken into account that developing seasonal weather forecasting is an ongoing process with still large uncertainty.

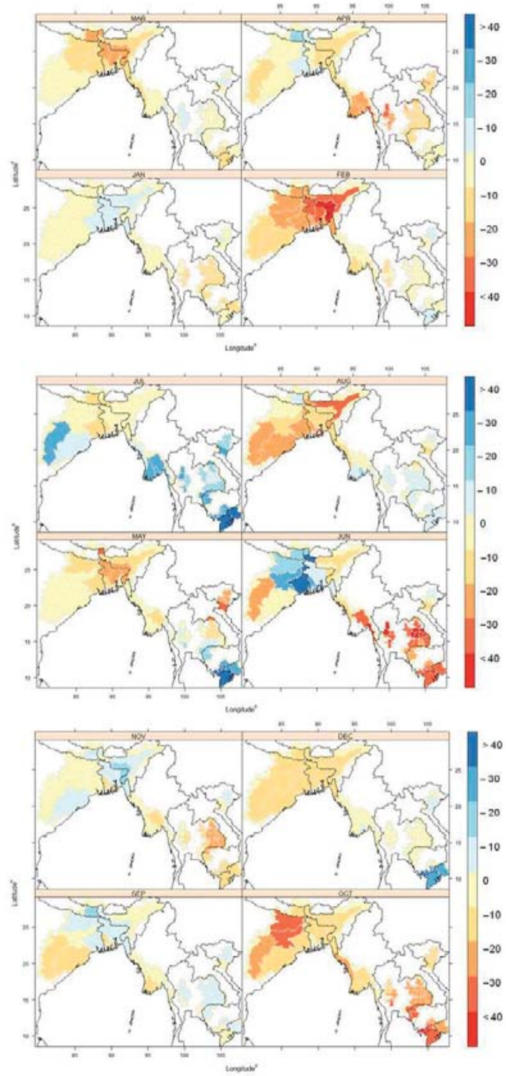

Fig. 2. Downscaled climate scenarios for January to December, based on an ensemble of 20 weather forecasts provided by NCAR for South and Southeast Asia.

Results

Considering the different ranges of resolution from ~1.1° × 1.1° up to ~2.8° × 2.8° and the related implications for different degrees of heterogeneity of underlying topography, as well as the proportions of land and ocean, it is impossible to use this projected climate information for sound location-specific agriculture adaptation options. For two rainfed environments, Cuttack (Orissa, India) and Rangpur (Rangpur District, Bangladesh), we analyzed time series of precipitation and maximum and minimum temperature. Table 3 summarizes the findings on precipitation trends for 2011-30 based on the congruence of these seven GCMs. This analysis of seasonal distribution of precipitation for seven GCMs shows the variability of mean monthly precipitation amount between the different GCMs, which is simulated for annual quarters: Jan-Feb-Mar (I, JFM), Apr-May-Jun (II, AMJ), Jul-Aug-Sep (III, JAS), and Oct-Nov-Dec (IV, OND).

The results show clearly that, for the regions of Cuttack and Rangpur, an agreement exists for a direction of change in the quarters I, II, and III because all or most GCMs indicate less rainfall in these months. Quarter IV (Oct-Nov-Dec) showed the highest degree of dissimilarity between different GCMs, which effectively impedes any reliable projection. In a parallel exercise, we downscaled future projections and mapped the changes to the observed baseline data on a subnational level. The results estimate that the mean monthly rainfall changes in the regional domains depending on the time of the year and location (Fig. 2). In South Asia (mainly eastern India and Bangladesh), reduced monthly rainfalls are indicated before the rice season (February, March, April, May), in the middle of the rice season (August),

Table 3. Comparative assessment of seven GCMs based on quarterly projections of precipitation for 2011-30; numbers denote the GCMs with lower (L), higher (H), and similar (≈) values as the CRU baseline. Numbers without brackets are a comparison of median values; numbers with brackets are a comparison of interquartile range.

Benchmark site	Jan-Mar			Apr-Jun			Jul-Sep			Oct-Dec		
	L	H	≈	L	H	≈	L	H	≈	L	H	≈
Cuttack, eastern India	7	0	0	6	0	1	4	2	1	3	2	2
(20º16´N, 85º31´E)	[7]	[0]	[0]	[6]	[1]	[0]	[0]	[0]	[7]	[7]	[0]	[0]
Rangpur, northwest Bangladesh	5	2	0	7	0	0	6	0	1	2	3	2
(25º45´N, 89º15´E)	[2]	[2]	[3]	[6]	[0]	[1]	[6]	[0]	[1]	[2]	[2]	[3]

and at the end (October). In Southeast Asia (mainly northeast Thailand, some parts of Myanmar, and northern Vietnam), reduced rains are predicted at the beginning of the rice season (April, May, June) and toward the end (October). Increased rainfall is mainly predicted for June (South Asia) and July (South and Southeast Asia). Thus, the mapping of changes in precipitation projected that the increase and decrease is varying throughout the months and regions, probably further increasing the severity and the areas already plagued by floods and droughts.

Climatology tools for forecasting climate extremes

Significance of drought in rice production

Drought causes substantial yield losses, even in subhumid rice-growing areas of Asia, and it is estimated to regularly affect 23 million ha of rice land (Pandey et al 2007a). More than 50% of this area is in China, where droughts cause economic losses that correspond to 0.5–3.3% of the agricultural sector gross domestic product. In India, particular drought years such as 1987 and 2002-03 have affected more than 50% of the total cropped area and almost 300 million people across the country (Pandey et al 2007b). In Thailand, the 2004 drought affected 20% of the rice land and more than 8 million people (Pandey et al 2007b). Even before a complete failure of a crop as in these cases, drought of milder intensity can also lead to substantial losses. The current projections of climate change scenarios include a strong likelihood of a shift in precipitation patterns in many regions. It is predicted that, by 2050, the area of land subjected to ‘‘increasing water’’ stress due to climate change will be more than double that with ‘‘decreasing water’’ stress (Bates et al 2008). Increased annual runoff in some areas is projected to lead to an increased total water supply, but this benefit is likely to be counterbalanced in many regions by the negative effects of increased precipitation variability and seasonal runoff shifts in water supply, water quality, and flood risks. Changes in water quantity and quality due to climate change are expected to affect food availability. Drought can be defined in different ways. From an agricultural perspective, drought corresponds to insufficient soil moisture to meet crop water requirements, thus leading to yield losses. Since this definition requires the consideration of various factors, including actual and potential evapotranspiration, soil water deficit, and related production losses, the mapping of drought over larger regions is usually done by simplified indices such as the Palmer Drought Severity Index, which gives an estimate of dryness based on observed precipitation and temperature data (PDSI, see Heim 2000). In eastern India, the economic cost of drought was found to be substantially higher than in other rainfed areas due to higher probability and greater spatial covariance of drought and less diversified farming systems (Pandey and Sharma 1996). In this part of India, rice accounts for a larger share of household income, which implies high risks for food security within the local populations. Although farmers deploy various coping mechanisms, these mechanisms are largely unable to prevent a reduction in income and consumption, especially in eastern India. In the eastern Indian states of Jharkhand, Orissa, and Chhattisgarh alone, rice production losses during severe droughts (about once every 5 years) average about 40% of total production, with an estimated value of US$800 million (Pandey et al 2007a). Bangladesh is affected by major country-wide droughts about every 5 years, but local droughts occur frequently and affect crop production life cycles at the respective location. Agricultural drought, related to soil moisture deficiency, occurs in Bangladeshi rice production at various stages of crop growth. Monsoon failure or late arrival often brings a yield reduction and famine to the affected regions (Asfaq et al 2009). A better understanding of the monsoon cycle as well as monsoon onset would clearly be of major scientific, agricultural, and social value. In northwest Bangladesh, the average annual rainfall varies between 1,500 and 2,000 mm, with more than 200 mm of rainfall per month during the monsoon period (June to September), when transplanted aman rice is grown mostly under rainfed conditions. However, the erratic rainfall distribution causes frequent droughts in this region, and results in yield losses that are generally higher than the damage caused by flooding and submergence (Towfiqul Islam 2008). A recent characterization and modeling study showed that the recurrence interval of drought is around 2 to 3 years, especially during the latter part of the aman crop, generally described as *terminal drought* (Towfiqul Islam 2008). Short-duration varieties such as BRRI dhan39 are used to escape this specific risk in this region but they are not very popular because of their lower yield potential in good years. However, the risk of early drought is also very serious because it prevents timely crop establishment. Early drought can be addressed with direct seeding and it is becoming more popular in some drought-prone regions. In Southeast Asia, northeast Thailand suffers considerably from severe drought in particular years, for example, 2004-05. The total economic costs of drought in northern Thailand, however, were found to be lower than in eastern India, in both absolute and relative terms (Pandey et al 2007b). In addition, household incomes in northern Thailand had a more diversified structure, making them less dependent on rice yields.

Raising productivity in unfavorable rice environments through tailored weather information for farmers

In rainfed rice environments, precipitation variability is by far the most important factor for variability in crop production and agricultural economic risk. To cope with this variability, a range of agricultural management strategies have been developed. These strategies are widely used in international dryland agriculture: for example, improved water-use efficiencies of plants, diversification of farming systems, crop rotation systems, and fallow management practices as well as advanced seasonal crop and climate forecasting systems. However, recent developments in the application of seasonal climate forecasts in the agricultural sector suggest that they offer a large potential for improved agricultural risk management, enabling farmers to tailor management decisions better to the next cropping season (Meinke and Stone 2005, Hansen 2005, Hammer et al 2001). Season- and region-specific prospects of agricultural production can be quantified using spatially explicit applied simulation models to predict crop yields and other biophysical response variables on a regional scale. Such regional simulation systems of crop productivity integrate long-term historical weather data, and, because of this, allow researchers to retrospectively investigate the potential value of seasonal climate forecasts for a particular decision problem (Meinke and Stone 2005). The integration of both seasonal and interannual climate forecasting and crop modeling becomes an integrated agricultural tool that gives information for increasing preparedness when facing climate variability and change in agricultural planning and operations. The seasonal climate forecast could become an extremely valuable tool—in terms of financial return on investment—if the generated information could be translated into distinct crop management strategies. Overall, especially for rainfed farmers in Asia, there is a need for information that is relevant at the field scale, and that is expressed in terms of impacts and management implications within the cropping systems that farmers manage (Hansen 2005, Meinke et al 2001). But, in practice, such specific and detailed information is rarely available to farmers, especially in rice-producing developing countries of Asia. This is partly because operational seasonal climate forecasts are typically given over large areas, resulting in inappropriate content, which is one of the obstacles to the adoption of seasonal climate forecasts by potential users (Nicholls et al 2000). If farmers of unfavorable rice environments would gain access to more timely and reliable seasonal rainfall forecasts, the risk of crop production could probably be significantly reduced by better matching the choice of crop and planting time to anticipated rainfall. This in turn could increase farmers' willingness and ability to invest in inputs such as high-quality seeds, fertilizers, and enhanced mechanization, allowing them to further increase crop productivity and achieve a higher income or degree of food security. At the same time, they could reduce labor and costs associated with replanting and would not need to fall back to shorter duration crops with lower yield potential, or even no crop at all.

Conclusions

The likely impacts of climate change on rice-based agroecosystems in Asia are very uncertain, especially for unfavorable environments and systems such as rainfed rice. To assess the regional impacts of climate change, one can typically downscale global circulation models. But reliance on a single GCM could lead to an unreasonable baseline for future adaptation options and thus ensemble projections for holistic adaptation options are arguably the best way to identify and operationalize future projections for regional applications. Probably the major challenge for raising productivity in rainfed environments will be through future tailored weather information, through a reduction in the complexity of this technology, and through the dissemination of these new knowledge technologies to farmers.

Scientific advances in meteorology and informatics have made it possible now to forecast drought with a reasonable degree of accuracy and reliability. Various indicators such as the Southern Oscillation Index are now routinely used in several countries to make drought forecasts. Suitable refinements and adaptations of these forecasting systems are needed to enhance drought preparedness at the national level as well as to assist farmers in making more efficient decisions regarding their choice of crops and cropping practices.

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Climate change and rice production in India: research and future strategies

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Climate change and particularly higher temperatures and increased incidence of drought, submergence, and salinity are expected to have a serious impact on rice productivity in India. To overcome these constraints, it is necessary to develop rice varieties with multiple stresses that incorporate *SUB1*, *Saltol*, and anaerobic germination (AG) within suitable genetic backgrounds. Specifically, this entails the development of varieties that can withstand prolonged submergence (beyond 15 days) in either clear or turbid floodwater. In view of the higher ambient temperatures likely to prevail, rice varieties are required that can retain fertility at higher temperature, fill grain with high day temperatures during the grain-filling stage, and maintain grain quality in these conditions. Crop and natural resource management options are required to provide adequate nutritional support to the growing crop and maintain system productivity. These challenges are regarded as realistic as rice is relatively resilient to many of the likely environmental stresses and moreover there is a large repertoire of germplasm to draw on to develop varieties suited to these adverse conditions. Combining germplasm development with crop management technologies can help sustain higher productivity, at least for the short term. Further advances are expected from varietal development facilitated by advances in biotechnology.

Ninety percent of the world's rice is produced and consumed in Asia, where irrigated and rainfed rice cultivation form the mainstay of food security in many countries. Climate change, however, could seriously threaten the production required to feed the burgeoning population of Asia. Increasing concentrations of greenhouse gases (GHGs), including CO_2, CH_4, and N_2O, are causing global warming along with consequences of shifts in rainfall pattern, melting of ice, a rise in sea level, etc. The impacts of these changes on agriculture are already being noted. There are considerable gaps in our knowledge of how agricultural production systems, including rice growing, will affect both short-term and long-term global food security. Although global circulation models (GCMs) predict opportunities for increased production, overall there appears little doubt that net agricultural production and productivity will be adversely affected by climate change. Determining how these changes can be handled and cropping systems adapted so as to sustain increased productivity in the face of the climate onslaught has now become an important research activity.

Several uncertainties exist regarding the accuracy of current projections on the impact of climate change on agriculture. Although one relates to the degree of temperature increase and its geographical distribution, the other relates to the concomitant changes likely to occur in the rainfall patterns that determine water availability to crops and the evaporative demand imposed on crops within a CO_2-enriched atmosphere. The problems of predicting the future course of agriculture in the changing world are compounded by the complexity of agricultural and socioeconomic systems that govern the world food supply and demand. Major changes in temperature, solar radiation, and precipitation will affect crop productivity. The magnitude and geographic distribution of such climate-induced changes might affect our ability to increase the food production required to feed the population of more than 10 billion projected for the middle of the century.

Indian research on climate change

Research on the impact of climate change and vulnerability of agriculture is a high priority in India, as the impacts, if true to the predictions, are expected to be widespread and severe. The agricultural sector represents 23% of India's gross national product (GNP), plays a crucial role in the country's development, and will continue to occupy an important place in the national economy. Agriculture sustains the livelihood of nearly 70% of the population. With rice covering the most important crop area (43.5 million ha), India is very dependent upon monsoon rains. Although analyses of food grain production/productivity trends in India for the last few decades reveal tremendous increases in yield, the vagaries of monsoon have had a negative impact in recent years as evidenced most recently in the failure of monsoon during 2009, when rice production declined to 84.5 million tons (projected) from the record 99.5 million tons of the previous (2008-09) year. In this context, a number of questions need to be examined to determine the nature of variability of important weather events, particularly the total amount of rainfall received during the season/year as well as its distribution within the season.

The mean temperature in India is projected to increase by 0.4 to 2.0 °C during kharif and 1.1 to 4.5 °C during the rabi season by 2070. Similarly, mean rainfall is projected to increase by up to 10% by 2070. There is also an increased possibility of climate extremes, such as the timing of the onset of monsoon and intensities and frequencies of drought and floods. Predictions by the IPCC for the Indian subcontinent indicate (1) an increase in ambient temperature, (2) a reduction in solar radiation, (3) a marginal increase in total precipitation, (4) an increase in ambient CO_2 concentration, and (5) frequent tropical disturbances in the coastal areas.

Climate change research in India began in the late 1980s with initial estimation of crop growth parameter modeling and its subsequent integration into climate models, and the quantification of GHGs from different cropping systems and their mitigation. Models suggest an increase of 1 °C in ambient temperature without any increase in CO_2 concentration resulting in a 5%, 8%, 5%, and 10% decrease in grain yield in the northern, western, eastern, and southern regions of the country, respectively. An increase of 2 °C resulted in a 10% to 16% reduction in yield in different regions, while a 4 °C rise resulted in a 21% to 30% yield reduction. It was reported that a 2 °C increase in mean air temperature could decrease rice yield by about 0.75 t ha^{-1} in the high-yield areas and by about 0.06 t ha^{-1} in the low-yield coastal regions (Sinha and Swaminathan 1991). Estimates of the impact of climate change on crop production could be biased depending upon the uncertainties in climate change scenarios, region of study, crop models used for impact assessment studies, and the level of management. Aggarwal and Mall (2002) studied the impact of climate change on grain yields of irrigated rice with two popular crop simulation models, CERES-RICE and ORYZA1N, at different levels of N management. Results suggest a direct effect of climate change on rice crops in different agro-climatic regions in India, which is expected to be positive in the face of various uncertainties. Depending upon the scenario, rice yields increased from 1.0% to 16.8% in pessimistic scenarios and from 3.5% to 33.8% in optimistic scenarios. These conclusions, however, are highly dependent on the specific thresholds of phenology and plant activity to changes in temperatures used in the models.

Emissions of CH_4 from Indian paddy are estimated by the United States Environmental Protection Agency to be 37.8 Tg. Scientists in different agricultural institutes, under the leadership of the Central Rice Research Institute, Cuttack, have made field estimates of CH_4 as well as N_2O, two important greenhouse gases emanating from agriculture. In a collaborative project led by the International Rice Research Institute, Philippines, a quantitative analysis of CH_4 estimations from Indian paddy fields was made. Under an IRRI-UNDP collaborative project, CH_4 flux from both rainfed and irrigated fields under the influence of different controlling factors such as organic amendments, water management, rice cultivars, and chemical inhibitors was quantified. In addition, studies were conducted to estimate the source strength of CH_4 for select Indian rice soils by measuring their CH_4 production and oxidation potentials and the factors influencing these processes. The results indicate that CH_4 emissions from the representative rainfed ecosystem at the experimental site averaged 32 kg CH_4 ha^{-1} $year^{-1}$ (Adhya et al 2000).

To ensure sustained high productivity, future farming systems will have to be better adapted to a range of abiotic and biotic stresses to cope with the direct and indirect consequences of a progressively changing climate. Intensively managed cropping systems, such as rice production, offer a variety of intervention points to adjust to projected climate change. With climate change, rice plants are anticipated to be affected by a variety of stresses, namely, heat, drought, salinity, and submergence. In view of wide adaptation to stresses, and its cultivation over a wide geographic area, rice offers the expectation that crops can be adapted to changing climatic conditions. Thus, while crop management adjustments can take care of marginal changes in climatic impacts, germplasm development and agronomic (crop and natural resource management) practices are expected to be major driving factors in combating the negative impacts of changed climate.

Advancement has taken place in Indian rice research, with strong input from the International Rice Research Institute, to adapt rice to stressed environments. Major achievements have been made in tackling the important abiotic stresses that are associated with anticipated climates, namely, drought, flooding, submergence, and salinity. These stress-tolerant improved varieties and crop management technologies are expected to improve rice productivity in different agroecological zones, thus allowing India to adapt to the changing climate.

Drought tolerance

Around 14 million hectares of rice in India are subjected to drought stress and, apart from around 7 million hectares of upland areas, other areas that are basically rainfed areas are subjected to drought at either the beginning or end of the season depending upon the late arrival or early retreat of monsoon. With the erratic nature of monsoon that is anticipated in the changed climate, a requirement of drought-tolerant rice cultivars will be highly felt. The Central Rice Research Institute, through its regional center at Hazaribagh, is working on identifying and developing drought-tolerant rice cultivars. One recent success has been the development of rice variety Sahbhagi dhan, whose name connotes its development from collaborative research, which is a drought- and blast-disease-tolerant, semitall, early-duration variety identified and released for cultivation in bunded uplands and rainfed shallow drought-prone lowlands of Jharkhand and Orissa.

This entry was developed following the pedigree method from the cross IR55419-04*2/Way Rarem, with IR55419-04 being the drought-tolerant donor. One drought-tolerant line with good phenotype from this cross, IR74371-70-1-1 (EC No. 91553), received from IRRI through an INGER nursery (IURON), was evaluated in the 2003 kharif season at Hazaribagh and found promising. Single plant selections were made from a bulk of the INGER nursery for further evaluation and for pure seed multiplication. The most promising line, designated as IR74371-70-1-1-CRR-1, was nominated for testing under a national trial. In the IRRI-India drought breeding network, in on-station breeding trials conducted at eight locations for three years (2005-07), it provided a yield advantage of 0.5 t ha^{-1} under moderate stress and 1.0 t ha^{-1} under severe drought conditions over IR64 and IR36, the two prominent varieties grown in these regions. Sahbhagi dhan flowers in 78–80 days, has intermediate stature (85–90 cm) and nonlodging characteristic with 5–8 effective tillers per plant, and possesses long bold grains. This variety is resistant to leaf blast and moderately resistant to brown spot and sheath blight. Features of long roots to extract moisture from deeper soil layers and ability to withstand 3 weeks of terminal drought make it an attractive candidate for fighting climate change–related erratic monsoon behavior, especially the early withdrawal of monsoon (Variar et al 2009, unpublished data).

The recent identification of a drought QTL (Steele et al 2006) and its use in a marker-assisted backcross program has allowed pyramiding of desirable traits to attain substantial improvements in rice-crop drought tolerance.

Submergence tolerance

With climate change, monsoon rains are expected to become more erratic, with changes in frequency, although the total seasonal rainfall might remain similar or marginally greater. Erratic monsoons and extreme weather events such as unexpected heavy rains inundated wider areas across many regions in Asia in recent times, causing flooding and submergence. In India, around 6 million hectares of rice area are affected by flash flooding in shallow and medium-deep water environments. In these situations, farmers are growing varieties moderately tolerant of submergence but these tend to have low yields. Most of the high-yielding varieties are not tolerant of submergence and the farmers growing them suffer from crop losses caused by periodic flash floods during the monsoon season. A major QTL (*SUB1*) that explains about 70% of the phenotypic variation in submergence tolerance has been identified and fine-mapped on chromosome 9 in the submergence-tolerant cultivar FR13A. Flood-Resistant 13A (FR13A) was released in Orissa State during 1968 for semideep areas and was developed through pureline selection from Kalambanka, a local traditional variety of Orissa. It is a long-duration variety, flowers in 130 days, and has long bold grains. FR13A is a submergence-tolerant lowland variety that overcomes submergence through a restriction in shoot elongation and carbohydrate consumption, thereby conserving energy reserves to enable recommencement of development upon de-submergence.

At the International Rice Research Institute, Philippines, this *SUB1* gene has been successfully introduced into six rice mega-varieties—Swarna, IR64, Samba Mahsuri, CR 1009, BR11, and TDK1—through marker-assisted backcross breeding. Among these, Swarna is the most popular high-yielding variety in rainfed shallow lowland areas in India and Bangladesh. The seeds of Swarna-Sub1 were received by CRRI, Cuttack, from IRRI, Philippines, under the ICAR-IRRI collaborative project "*From genes to farmers' fields: enhancing and stabilizing productivity of rice in submergence-prone environments*" during 2005 (Reddy et al 2009). These seeds were multiplied and supplied to different research institutions, including NDUAT, Faizabad (Uttar Pradesh); RRS, Chinsurah (West Bengal); RRS, Patna (Bihar); ANGRAU, Andhra Pradesh, at their request. It was also tested in different states of eastern India (Assam, Bihar, Orissa, West Bengal, Chhattisgarh, and eastern Uttar Pradesh) under the Eastern India Rainfed Lowland Shuttle Breeding Network (EIRLSBN) between 2006 and 2008. Swarna-Sub1 was nominated for testing under the All India Coordinated Rice Improvement Program (AICRIP) during 2007 and 2008. Swarna-Sub1 along with other two Sub1 lines, IR64-Sub1 and Samba Mahsuri-Sub1, are under testing in an AVT 2-NIL-submergence trial during the kharif season under AICRIP.

On-station evaluation of Swarna-Sub1 by the Central Rice Research Institute (CRRI), Cuttack (Orissa), indicated that the incorporation of the submergence-tolerance gene *SUB1* has no deleterious effects on yield and its attributes (Sarkar et al 2009). The results also indicated that growing of varieties with *SUB1* in areas that are frequently subjected to flash floods will benefit the farmers and help to improve their livelihood in unfavorable rainfed lowland areas in eastern India. Swarna-Sub1 is suitable for flash-flood areas as a replacement for Swarna. It is not, however, suited for areas where submergence is followed by prolonged waterlogging.

The incorporation of *SUB1* into other popular lowland rice varieties (Gayatri, Sarala, etc.) using molecular (marker-assisted backcross breeding) as well as conventional approaches is in progress at CRRI, Cuttack.

Salinity tolerance

The increasing threat of salinity is an important issue linked to climate change. A rise in sea level due to global warming is anticipated to inundate coastal areas that have rice cultivation (Wassmann et al 2004). Salinity is the most widespread soil problem and it affects more than 800 million ha (7%) worldwide, and this problem is increasing due to soil and groundwater salinization. In South and Southeast Asia, more than 27 million ha of rice lands are salt affected and, in such areas, low or high soil pH, nutrient deficiencies/toxicities, drought, submergence, and waterlogging are additional problems that reduce crop productivity. These salt-affected areas are predominantly inhabited by poor communities with limited opportunities for improved food security and livelihoods.

Rice is a moderately salt-sensitive crop with a threshold electrical conductivity of 3 dS m^{-1}. Rice is particularly sensitive to salt stress during early seedling and reproductive stages. Good progress, however, has been made in developing salt-tolerant varieties using conventional and molecular approaches. A major QTL for salinity tolerance (*Saltol*) at the seedling stage mapped on chromosome 1 is being transferred to popular varieties at both IRRI and NARES research centers. Work is in progress for the identification and mapping of additional QTLs for seedling-stage tolerance and QTLs for reproductive-stage tolerance.

The Central Rice Research Institute, Cuttack, in collaboration with IRRI has evaluated 33 genotypes from INGER (IRSSTN) in farmers' fields under high salinity (soil ECe at planting of 15.4 dS m^{-1} and field water EC during crop growth of 6.5–9.2 dS m^{-1}). Among the different lines tested, IR71907-3R-2-1-1 produced higher grain yield than IR72046-B-R-3-3-3-1. Salt-tolerant donors FL 378, FL 478, and FL 496 and popular varieties Gayatri, Savitri, Sarala, Varshadhan, Naveen, and Khandagiri were used for genotyping of the *Saltol* locus. MAS protocols for the introgression of salt-tolerance QTLs have been standardized and at least three markers (RM 10711, SKC 10, and RM 8094) could distinguish the tolerant and sensitive genotypes. It is expected that salt-tolerant rice varieties will be available in the near future. Pyramiding of *Saltol* and *SUB1* QTLs into popular varieties to withstand flooding with salt water, especially in coastal areas, is also in progress and some lines developed at IRRI are being tested in the field.

Future strategies

Climate change is a reality and agriculture is expected to be seriously affected. Variable climatic conditions are likely to affect the yield and productivity of crop plants, including rice. Although rice has a certain degree of resilience, such characters are required to be enhanced by increasing tolerance of the individual stress as well as multiple stresses. Considering the major impacts of climate change, including high temperature, drought, submergence, and salinity, on rice production and productivity, we have to select options to fast-track the improvement options. Some future strategies could include

1. Developing rice varieties tolerant of multiple stresses by incorporating *SUB1*, *Saltol*, and anaerobic germination (AG).
2. Developing varieties that can withstand prolonged submergence (beyond 15 days) and that are tolerant of clear and turbid floodwater.
3. In view of the higher ambient temperatures likely to prevail, developing varieties that can retain fertility at higher temperature, fill grain with high day temperatures during the grain-filling stage, and maintain grain quality in these conditions.
4. Developing appropriate CNRM technology to provide maximum nutritional support to the growing crop.
5. Developing and adapting farmer-friendly strategies for growing crops in changed climatic conditions.

Conclusions

Changing climatic conditions are predicted to negatively affect agricultural production, and it is a challenge and it is the responsibility of scientists and policymakers alike to act to sustain higher productivity in the rice sector. Rice is relatively resilient to many of the likely environmental stresses and, moreover, there is a large repertoire of germplasm to draw on to develop varieties suited to adverse conditions. A judicious mix of germplasm exploration and crop management technologies can sustain higher productivity, at least for the short term, and further advances are expected from varietal development facilitated by advances in biotechnology.

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The role of stress-tolerant rice varieties for adapting to climate change

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One of the main consequences of climate change that will affect rice is the increase in the frequency and severity of abiotic stresses. Higher temperatures will have particularly adverse effects in the tropics. In addition, extreme weather events will result in more frequent droughts and floods. Rising sea levels will cause salinization of many rice lands. Tolerances of all of these abiotic stresses are present in rice germplasm, although the widely grown cultivars are generally sensitive. This tolerance can be bred into new varieties using conventional breeding methods or marker-assisted backcrossing (MABC). This work has been in progress for the unfavorable rainfed rice areas, and new drought-, submergence-, and salt-tolerant rice cultivars are now being developed. These improved lines being developed for rainfed environments will have wider applicability in the future, and will help to mitigate the effects of climate change on rice production.

Breeding for tolerance of abiotic stresses has been an important objective for rice breeders for many decades, and was particularly amplified during the 1970s. At that time, modern high-yielding varieties (HYVs) were being rapidly adopted in irrigated and favorable rainfed areas, but farmers in the more unfavorable areas continued to grow traditional varieties. HYVs have continued to spread into both irrigated and rainfed areas, and now constitute the vast majority of varieties grown in tropical Asia. However, these varieties are invariably intolerant of the abiotic stresses that afflict farmers in the more unfavorable rice-growing environments. Drought, submergence, and salinity stresses reduce yields on millions of hectares of rice production, and, despite efforts for more than 30 years to develop tolerant varieties, farmers still grow susceptible varieties or low-yielding local landraces.

The prospect of global warming attributed to the accumulation of greenhouse gasses is causing major concern, especially in connection with its effects on food production. Increasing temperatures will have a negative impact on rice production in the tropics, where most of the world's poor live. Rising sea level will result in the loss of some of the lands currently used for the production of major crops such as rice, and will impede drainage, leading to more flooding problems in coastal areas. More erratic rainfall patterns will result in greater frequencies of both drought and floods, and higher temperatures will reduce the yields of rice crops.

The scenario of climate change is leading to a convergence between ongoing efforts to develop appropriate varieties and production practices for the more unfavorable rice-growing areas and efforts to develop crops adapted to future climate change. Rice varieties tolerant of the major abiotic stresses of drought, flooding, salinity, and high temperature will provide some protection against the effects of climate change. Fortunately, recent progress in developing stress-tolerant varieties permits some optimism about the prospects for developing "climate-proof" rice varieties. Projects such as the Consortium for Unfavorable Rice Environments (CURE) funded by the International Fund for Agricultural Development and Stress-Tolerant Rice for Africa and South Asia (STRASA) funded by the Bill & Melinda Gates Foundation are making rapid progress in providing technology for farmers in the unfavorable areas. Our article reviews some of the advances made in genetics and breeding for stress tolerance in rice.

Drought tolerance

Drought is the most serious constraint to rice production in unfavorable rice-growing areas, and most of the popular farmers' varieties are susceptible to drought stress (Serraj et al 2009). Genetic studies through QTL mapping have been conducted intensively over the last 20 years. These studies have focused on the direct measurement of yield under drought stress as well as secondary traits such as root characteristics and leaf rolling. For nearly all traits, QTLs with relatively small effects are common, and different QTLs are often detected in different studies (Lafitte et al 2006, Bernier et al 2009).

These small QTLs have not been considered very useful for breeding purposes. However, some studies using direct measurement of yield under drought stress have shown promising results in identifying QTLs with a major effect on grain yield under drought. Bernier et al (2007) detected a QTL on chromosome 12 using a large population from the cross of Vandana/Way

Rarem. This QTL accounted for about 50% of the genetic variance, and was expressed consistently over 2 years. This QTL seems to increase the water uptake of plants under water stress (Bernier et al 2009). A QTL near the *sd1* semidwarf gene had a large effect on grain yield under lowland drought. A QTL on chromosome 3 had a large effect on drought tolerance in the cross between tolerant variety Apo and the widely grown variety Swarna (Venuprasad et al 2009). This QTL shows a high potential for applications because variety Swarna is widely grown in drought-prone environments, and it has high yield in addition to other desirable traits.

Conventional breeding for drought tolerance has been successful recently, and drought-tolerant varieties such as Sahbhagi Dhan (IR74371-70-1-1), Sahod Ulan 1 (IR74371-54-1-1), and Tarharra 1 (IR84011-B-49-1), recently released in India, the Philippines, and Nepal, respectively, are being disseminated to farmers in drought-prone areas. These varieties perform well even during favorable years, and they can provide about a 1 t/ha yield advantage under stress. Most of the popular varieties collapse under these conditions.

Submergence tolerance

Submergence can affect rice crops during any stage of growth and can be short-term, sometimes referred to as flash flooding, and longer-term, known as stagnant flooding. Most studies focus on submergence tolerance at the vegetative stage, which is the most common problem. Highly tolerant varieties such as FR13A from Orissa, India, have been used as sources of tolerance in breeding programs. These varieties possess the *SUB1* gene on rice chromosome 9, which is an ethylene response factor-like gene (Xu et al 2006). The level of tolerance is related to the degree of expression of this gene, which is associated with a suppression of the normal elongation response of rice varieties when under water. This suppression of elongation enhances survival by reducing carbohydrate consumption, allowing the plants to recover upon de-submergence (Fukao and Bailey-Serres 2008). The *SUB1* gene has been transferred into a number of widely grown varieties by marker-assisted backcrossing (MABC) (Neeraja et al 2007, Septiningsih et al 2009) (Table 1). Fortunately, this gene works well in any genetic background, and does not affect yield potential.

Tolerance during germination and early seedling growth is important for direct seeding, under both irrigated and rainfed conditions (Ismail et al 2009). Varietal differences for submergence tolerance during germination have also been observed, and this trait is not related to tolerance during vegetative growth; however, breeding lines that combine tolerances at both stages were recently developed. Some major QTLs have been identified for this trait (Angaji et al 2010), and improved breeding lines have been developed. However, these have not yet been validated under farmers' field conditions. Besides genetic tolerance, proper seed and seedbed management of these tolerant lines seems to be essential for sufficient tolerance to be expressed under field conditions (Ella et al 2010).

Longer-term "stagnant" flooding is common in low-lying areas, and is expected to be an increasing problem in delta areas, such as the Ganges, Mekong, and Ayeyarwaddy, which will be affected by rising sea level. If the water level remains at around 50 cm or lower, then improved varieties with submergence tolerance and taller plant height will be appropriate for these areas. These varieties also need traits specific for these conditions, such as ability to survive and tiller well under deeper water levels and resistance to lodging. If the water level goes beyond 50 cm for longer periods, rapid elongation ability is necessary to keep up with rising flood water. These varieties initiate internode elongation early in their growth period and have a rapid rate of internode elongation. The early initiation of elongation is controlled by QTLs on chromosomes 3 and 12 (Nemoto et al 2004, Hattori et al 2007, Kawano et al 2008). The rate of internode elongation is controlled by QTLs on chromosomes 1 and 12 (Hattori et al 2007, 2008, Kawano et al 2008). The chromosome 12 QTL appears to have a major effect in the rapid elongation response of deepwater varieties. The major locus on chromosome 12 was shown to have two ERF genes, named *SNORKEL1* and *SNORKEL2*, which controlled this elongation response (Hattori et al 2009). The genes are similar to *SUB1* but the latter seems to suppress elongation.

Table 1. Improved varieties and breeding lines with the *SUB1* gene for submergence tolerance.

Breeding lines with *SUB1*	Maturity (days)	Plant height (cm)	Amylose (%)
IR64-Sub1 (IR07F102)	112–116	90–95	22
Swarna-Sub1 (IR05F102)	130–134	75–85	27
S. Mahsuri-Sub1 (IR07F101)	126–134	80–85	25
TDK1-Sub1 (IR07F289)	139–144	106–125	Waxy
BR11-Sub1 (IR07F290)	128–130	130–134	24
CR1009-Sub1 (IR07F291)	153–154	122–125	25
PSB Rc68 (IRRI 119)	118–121	121–125	26
INPARA-3 (IR70213-9-CPA-12-UBN-2-1-3-1)	114–116	110–114	25
Ciherang-Sub1 (IR09F436)	112–115	115–119	21
PSBRc82-Sub1 (IR09F434)	115–118	102–105	20

Development and use of varieties with the *SUB1* gene have been a great success, and several have been released (for updates, see www.irri.org/flood-proof-rice/). These varieties typically have a 1–2 t/ha yield advantage over the susceptible varieties, but can give much higher benefits under more severe submergence stress (Sarkar et al 2009, Singh et al 2009).

Salt tolerance

Salt stress-prone lands include the inland saline/sodic areas, which require irrigation for reclamation, and coastal areas subject to salt-water intrusion. In the latter case, salinity generally increases in the dry season, and declines during the rainy season. Nevertheless, varieties for both seasons require tolerance of salinity. A major QTL was identified conferring salt tolerance on chromosome 1 and designated *Saltol* (Bonilla et al 2002), and this has been the target of marker-assisted selection (Thomson et al 2010). One chromosome 1 QTL, *SKC1*, was isolated by positional cloning and determined to be a protein that functions as a Na^+-selected transporter (Ren et al 2005). Besides *Saltol*, several other major QTLs are being identified and targeted for MABC, to combine them with *Saltol* for higher tolerance.

Considerable progress has been made in developing improved varieties with tolerance of salinity, particularly for the inland saline/sodic areas (Singh and Mishra 2006, Rao et al 2008). Furthermore, the same approach used for developing submergence-tolerant mega-varieties is being used for salinity with the *Saltol* locus (Thomson et al 2010). For coastal areas in the wet season, both salinity and submergence are problems. Recent work at IRRI has shown that the *SUB1* gene and *Saltol* can be combined in the same genotype, and these lines combine tolerance of both stresses (R.K. Singh, personal communication).

Heat tolerance

High-temperature stress is not considered a current limitation for rice production except in a few areas where rice is grown in hot dry environments. However, most rice varieties are very sensitive to high temperatures. Temperatures above 35 °C generally cause sterility if they occur during anthesis, which is usually complete before 1100 in most tropical or warmer environments. Thus, temperatures need to be above a maximum of 40 °C before appreciable effects can be seen on sterility (Yoshida et al 1981). However, higher night temperatures in tropical regions during the ripening stage decrease rice yields appreciably (Peng et al 2004). Higher temperatures also cause deterioration in grain quality (Counce et al 2005, Zhong et al 2005, Tanaka et al 2009).

Donors for tolerance of high temperature during anthesis have been identified and initial genetic studies carried out (Satake and Yoshida 1978, Mackill et al 1982), but QTL mapping is still under way. From preliminary analysis, it appears that QTL introgression approaches may also be feasible for tolerance of high temperature in rice.

Conclusions

Rapid progress has been made to incorporate tolerance of the stresses of drought, submergence, and salinity into improved varieties, and many of these are now being disseminated to farmers in the unfavorable regions. These varieties have the potential to give at least a 1 t/ha yield advantage under stress conditions, while performing similar to or better than the farmers' present varieties under favorable conditions. To ensure that future rice varieties are adapted to forecasted changes in climate, these tolerances should be built into all improved rice varieties in the future. Additional efforts need to focus on identifying new genes/QTLs for stress tolerance so that they can be pyramided into elite genetic backgrounds and make further improvements in rice productivity under stress.

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Crop and natural resource management for climate-ready rice in unfavorable environments: coping with the adverse and creating opportunities

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Climate change is anticipated to affect rice production is Asia through increasing average and maximum temperatures, increased and less evenly distributed rainfall, and rising sea-water levels. These changes are expected to aggravate the abiotic stresses that already affect large areas in unfavorable rice environments, especially drought, submergence, and salinity. This review provides an overview of existing crop and natural resource management (CNRM) technologies to help rice cope with widespread abiotic stresses and to open new opportunities for intensification and diversification of the cropping system. In addition, mitigation options to reduce the contribution of rice-based cropping systems to climate change are described.

Drought is the most common abiotic stress in rainfed lowland and upland rice environments. Although water scarcity is an increasing problem in many regions, where feasible, further establishment of at least partial irrigation capacities from shallow tube wells and water harvesting remain a good option for many areas. Other possibilities to reduce the effect of drought are adjusted cropping patterns, improved nutrient supply and nutrient management strategies adjusted to available water resources, land leveling, and soil improvement. Where limited irrigation water is available, water-saving irrigation techniques can help to make the best use of the available water resources. Narrowing yield gaps in flood-affected areas can be achieved by combining high-yielding varieties with submergence tolerance and shorter duration with proper crop management. This includes proper seed and seedbed management practices; direct seeding, which can help to have taller, less susceptible plants when the floods arrive; and higher fertilizer use and stress-adjusted nutrient management increase plant survival and recovery. In some areas, dry-season rice has become a major crop in some flood-prone regions, transforming farmers' livelihood, and this option has substantial potential in many other areas. Salinity is an important problem in many coastal regions but also in dry inland areas. An array of technologies has been developed, including improved agronomic options, water harvesting and water management, soil salinity management, and proper choice of cropping patterns. Infrastructure that allows drainage but restricts intrusion of saline water, thereby reducing salinity and halting further degradation, can also be a critical component to improve productivity. Adjusted water, residue, and fertilizer management is the main management element that can be used to mitigate climate change. Mitigation options should be concentrated on intensive irrigated areas as most gains can be made in these systems. Careful account needs to be taken of the numerous interactions between crop management and the expected changes in climate.

Keywords: biochar, climate change, crop management, drought, rice, rice residues, salinity, submergence, unfavorable environments

Unfavorable rice environments are defined as those areas where rice production is frequently constrained by abiotic stresses such as drought, submergence, and adverse soil conditions. Most of these conditions are found where rice production is dependent on rain only, as in rainfed rice, but these also occur in irrigated or partially irrigated systems. The most important rice-based rainfed system in Asia with respect to area and the number of dependent households is the rainfed lowland ecosystem, which covers about 46 million hectares or almost 30% of the total rice area worldwide (Fig. 1). Other rainfed systems comprise upland rice (about 8.9 million hectares in Asia) and deepwater rice (about 3.7 million hectares in Asia) and, in these areas, multiple abiotic constraints often prevail. Considerable areas of unfavorable rice environments in irrigated systems are constrained by submergence, soil salinity, acid sulfate soils, and peat soils. Many of these rice areas are located in deltaic and coastal regions. The most important abiotic stresses that affect

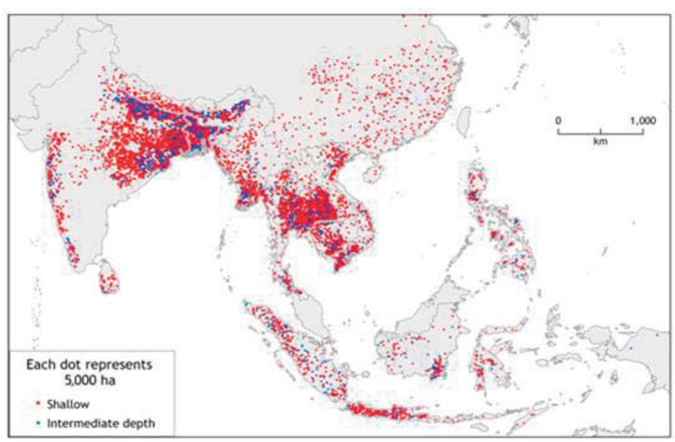

Fig. 1. Distribution of rainfed lowland rice environments across Asia, separated for shallow (0.1–0.3 m, usual water depth) and intermediate (0.3–1 m, usual water depth) rainfed lowlands, modified from Haefele and Hijmans (2007).

rice production are drought (approx. 23 million ha regularly affected), submergence (approx. 20 million ha regularly affected), and salinity (approx. 15 million ha affected).

Climate- and soil-related abiotic stresses are already widespread in rice-based cropping systems in Asia. Climate change, which is predicted to cause higher temperatures, more extreme rainfall events, and a considerable rise in sea level, is likely to result in these stresses becoming more common and more severe. To address the existing and future abiotic stresses in unfavorable environments, a combination of improved germplasm and adjusted crop and natural resource management (CNRM) options are necessary. Recent advances in germplasm development indicate considerable progress in submergence, salinity, and drought tolerance of new rice varieties (Ismail et al 2007, 2008, Septiningsih et al 2009, Verulkar et al 2010, Thomson et al 2010). To complement these varietal developments, improved options for CNRM need to be developed and disseminated together with the new varieties. In the following, we provide an overview of promising CNRM technologies that help rice to cope with common abiotic stresses, enhance the tolerance of the new rice varieties, and open up new opportunities for intensification and diversification of cropping systems. We also discuss some CNRM options for climate change mitigation in rice-based systems. Thereby, we hope to provide an overview of the role of rice CNRM in climate change adaptation and mitigation, and to highlight the potential contribution of this research in unfavorable rice environments.

Possible effects of climate change in unfavorable rice environments

Climate change is an irregular and relatively slow process from a human perspective, even if it may be rapid from a geological point of view. Predictions of the effects of climate change are often given for relatively distant future dates, for example, for 2100. But, for the development of modified CNRM options, mainly changes in the near future are relevant, perhaps within the next 10 to 20 years. Also, likely developments in this shorter time frame can be more reliably estimated based on existing trends.

Increasing temperature is a potential threat to rice production as high temperatures can affect the rice crop at all stages of development, particularly during flowering, when it causes spikelet sterility. Higher temperatures also increase respiration of the plant, affect photosynthesis, and shorten the grain-filling period, all of which reduce grain yield (Peng et al 2004). Very high temperatures (> 33 °C) already occur in some Asian rice-growing regions but these are mostly limited to the dry-season irrigated rice crop. Critically high temperatures in the wet season are unusual, and high temperatures alone are unlikely to become a major constraint in unfavorable rice areas within the next 20 years. However, even limited temperature stress can be aggravated by drought as rice plants lose the ability to cool through transpiration, and the combination of both elements could cause more frequent temperature damage in rainfed rice crops (Wassmann et al 2009).

The same authors conclude that, in the near future, changes in precipitation may have a greater impact on agricultural production than temperature changes. It is generally agreed that global climate change will cause a higher global average rainfall. Nevertheless, most studies assume that the effects of increased precipitation variability and intensity will increase the occurrence of drought. It has been shown that the production of rice, maize, and wheat has already declined in many parts of Asia in the past few decades due to increasing water stress, arising partly from increasing temperatures, increasing frequency of El Niño events, and a reduction in the number of rainy days (Aggarwal et al 2000, Fischer et al 2002, Tao et al 2004).

More frequent high-intensity rainfall will increase the incidence of flood events in the lower landscape portions in inland areas, thus increasing the occurrence of submergence events. Further, coastal and deltaic regions will increasingly be affected by the rising sea levels. Although the expected average sea-level rise in the coming 20 years is not large, with mean estimates of 32–62 mm based on the observed trends in the last century/decade, this is aggravated by sinking land areas in most large Asian deltas (Syvitski et al 2009). Combined, these trends will affect the drainage of inland water, causing saline intrusion in rivers during the dry season and increasing the threat from extreme weather events. It is assumed, therefore, that rice production in coastal and deltaic regions will increasingly be affected by submergence and salinity (Wassmann et al 2004, 2009, Bates et al 2008). Similarly, Allen et al (1996) concluded that the future challenge for irrigation systems in coastal/deltaic regions may primarily be the prevention of salinity intrusion and excessive flooding.

CNRM options to adapt to and cope with the adversity of climate change

Drought-prone environments

India has the largest area of drought-prone rainfed lowland rice (13.3 million hectares), followed by Thailand (8.2 million ha), but there is also major rainfed lowland rice in Bangladesh (5.1 million ha), Indonesia (4.0 million ha), Vietnam (2.9 million ha), Myanmar (2.4 million ha), Cambodia (1.6 million ha), and the Philippines (1.3 million ha) (see Fig. 1 and Haefele and Hijmans 2007). Drought has long been recognized as the primary constraint to rainfed rice production. It can occur at any time during crop growth and is highly variable in space and in time. Drought can decrease rice yields directly by reducing transpiration or causing spikelet sterility, or indirectly by impeding management operations such as crop establishment or weeding, or by favoring low-input strategies.

One way to escape drought is to establish irrigation facilities, an approach used in many previously rainfed lowland systems, and this contributed to large productivity increases. Examples are the establishment of large numbers of tube wells in eastern India and Bangladesh. Another possibility is the harvesting and storage of rainwater, with examples in northeast Thailand, some regions of eastern India, the Philippines, and Indonesia, where considerable numbers of village and farm ponds for rainwater harvesting were established (Haefele et al 2009).

If drought patterns are relatively stable in either the early season or late season, drought avoidance can be achieved by adjusting the cropping season to the intervals when rainfall and water availability are most favorable. Alternatively, the length of the cropping season, and thereby the drought risk, can be adjusted with the help of short-duration varieties or nonphotosensitive varieties. Although these may seem obvious options, in many rainfed lowlands long-duration photosensitive variety types are still predominant and no good short-duration materials are available to farmers.

Improved nutrient management is another important mechanism to moderate drought damage. Although nutrient management is rarely seen as an option to mitigate drought stress, nutrients are often a limiting factor in rainfed lowlands. Limited growth reduces access to available soil water resources and drought stress further decreases the plant availability of nutrients (Haefele and Bouman 2009). Improved nutrition makes the plants a stronger competitor for water and helps to reduce unproductive water losses (Fig. 2). These effects obviously cannot help in the case of extreme drought or drought around flowering time but medium drought events with considerable yield-reducing effects are common in many rainfed lowlands.

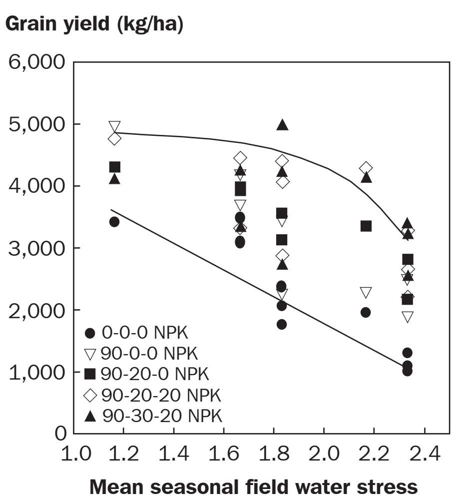

Fig. 2. Grain yield across six sites and different fertilizer treatments but dependent on the mean seasonal field water stress (Pangasinan, Philippines, 2009 wet season). Field water stress levels were scored according to 1 = permanently flooded, 2 = permanently wet soil surface, and 3 = permanently dry soil surface. The figure indicates that normal fertilizer use can contribute considerably to reduce the negative effect of drought stress on grain yield. The envelope lines indicate the trend for unfertilized and fully fertilized treatments.

Direct seeding rather than transplanting provides other opportunities to reduce unproductive water losses and moderate drought effects. Dry direct seeding (DDS) allows earlier establishment than transplanting, thus reducing deep percolation and evaporation losses from early-season rains. The advantages were analyzed by Rathore et al (2009) for four different establishment methods of rainfed rice in eastern India (Table 1). Sowing dry rice seed in dry soil could be undertaken before the rains have started, whereas sowing dry seed in moist soil, as with the *biasi* system, requires 112 mm of water on average. In comparison, crop establishment by transplanting (including the then necessary soil puddling) and wet plowing in the biasi system require approximately 500 mm of rainfall. Rice established by DDS on dry soil suffered less from water deficit, resulted in better rainfall-use efficiency, and gave the best yields across the 5 years of the study. Research on minimum- or zero-till options for rice is ongoing but no conclusive results for a range of conditions are available yet.

Land leveling and soil improvement are other management methods tested in rainfed rice to increase water productivity, making better use of available water and reducing water losses. Land leveling can be optimized with laser-guided equipment but better field leveling can often be achieved with conventional farm equipment. Application and incorporation of organic or clayey materials can help increase soil-water retention capacity, especially on coarse-textured soils. Where at least partial irrigation is possible, water-saving irrigation techniques such as alternate wetting and drying (AWD), saturated soil culture (SSC), and aerobic rice are possible options to make best use of scarce water resources (Bouman 2007).

Upland environments

In South and Southeast Asia, more than 40 million people directly depend on the marginal uplands for their food needs. Uplands are highly heterogeneous with varying elevations and climate that range from humid to subhumid, and soils varying from fertile to infertile. Rice is a major food crop in this environment, and thus the food security of the people depends on rice production. Rice-based farming systems under shifting cultivation account for more than 3 million ha in northern Vietnam, Lao PDR, Nepal, and northeastern India. In Yunnan, China, upland rice has been grown for more than 4,000 years under shifting

Table 1. Average time of establishment and corresponding cumulative rainfall in five seasons (1995-2000) depending on the rice establishment method in an on-station experiment at Raipur, Chhattisgarh, India. For all establishment methods, rice was grown under rainfed conditions without irrigation.

Establishment method[a]	Event[c]	Day of year	Cumulative rainfall in mm
DDS dry	Sowing	159	0
	Establishment[b]	177	131 ± 51
DDS moist	Sowing	180	134 ± 55
	Establishment[b]	195	261 ± 61
DDS biasi[b]	Sowing	174	113 ± 52
	Establishment[b]	193	255 ± 60
	Biasi-operation	219	532 ± 106
T	Transplanting	219	496 ± 112

[a]Establishment methods were dry direct seeding in lines and dry soil (DDS dry), dry direct seeding in lines and moist soil (DDS moist), dry direct seeding broadcast in moist soil and biasi operation (DDS biasi), and transplanting (T). [b]1998-2000 only. [c]Establishment refers here to a plant size comparable with the seedling size at transplanting.

cultivation based on slash-and-burn systems with rice as one of the staple food crops in the southern part (Tao et al 2009). In this region, upland rice area has been stable at 100,000 ha, with an average yield of 2.5 tons/ha. In Indonesia, rice production has also remained almost constant at 1.2 million ha, although an upland area of about 5 million ha could be used for food crop production (Suwarno et al 2009). Compared with other countries, the Philippines has an upland area of 160,000 ha only, but, like most upland areas in South and Southeast Asia, these areas are home to farmers who are socially and economically marginalized and often among the poorest. To address changing climate and to help alleviate poverty in these upland systems, approaches can be directed toward landscape management, and embrace strategies that include productivity growth, income enhancement, and resource conservation.

Challenges to growth in rice yield in the uplands are drought, weeds, blast, nematodes, and poor soil fertility, in which soils are deficient in phosphorus and generally acidic (Piggin et al 1998). In addition, soil erosion is a problem associated with sloping uplands, and may be exacerbated by climate change when left unabated. In Yunnan, some sloping fields have been converted into terraces to control water and soil erosion, and farmers use agricultural implements and input-responsive varieties to increase yield. Together with germplasm improvement, strategies to improve soil fertility status have provided opportunities for increasing the productivity of rice and other crops. Thus, like other environments prone to the adverse effects of climate change, crop management has to incorporate climate-ready resilient varieties that are drought resistant along with a combination of traits such as weed competitiveness, resistance against predominant pathogens such as blast or brown spot, responsiveness to low fertilizer inputs, tolerance of soil problems caused by low pH, and good grain quality that matches preferred traditional varieties in the region. In Laos, for example, grain yield of improved and traditional glutinous and nonglutinous cultivars increased with fertilizer application (e.g., 50-30-30, 50-50-50) and, in northeastern India, an NPK rate of 20-10-10 has been applied to increase the yield of improved upland varieties (R. Sarma, personal communication). Additionally, short-duration varieties that mature before the end of the rainy season could escape the more damaging late-season drought.

Landscape management for crop production, especially with limited water resources, can lead to improved production, particularly when emerging biotic constraints are addressed. Although water-saving irrigation techniques are valuable for improving water productivity as in the drought-prone bunded uplands or in the aerobic rice system, a number of pests can exert deleterious effects on the rice crop under these conditions (Zeigler 2007). Examples of emerging pests are root-rotting fungi such as *Pythium arrhenomanes* and root-knot nematodes (RKN) such as *Meloidogyne graminicola* (Van Buyten et al 2011, Win et al 2011). These organisms have been shown, at least in part, to reduce yield in aerobic rice (Kreye et al 2009) while they pose no problem in conventional paddy rice. The relative influence of these two organisms on the growth of aerobic rice variety Apo as seen in the field was confirmed in a study in controlled conditions. This study also compared the responses of traditional upland rice varieties and an IRRI rice line to simultaneous inoculation of both organisms. The study showed that the presence of both organisms does not always cause more severe disease symptoms. Tolerance of or resistance to one may help in alleviating the symptoms in the other. However, if the plant is less than tolerant of both, the combination of the two pathogens aggravates the disease symptoms caused by either one. Besides potential aerobic rice varieties that produce high yield despite these emerging diseases, a promising management option for aerobic rice is the addition of organic matter through *in situ* composting of crop residues (Banaay 2011). This is able to significantly reduce the severity of root galling caused by RKN and reduce the occurrence of *Pythium* sp. in roots of aerobic rice variety Apo.

Weeds pose a major constraint to upland rice production. To characterize weed infestations under different conditions in the upland rice environment, trials were conducted in northern Laos in three positions on the toposequence and after different fallow periods in farmers' fields (L. Khangxeuthor and K. Songyikhangxeuthor, unpublished results). Weed biomass was higher in 3-year continuous cropping and a 2-year fallow period. In farmers' fields after a long fallow period, weed biomass tends to be lower. Weed biomass varied between the two sites (Xieng Ngeun and Pack Ou districts) and toposequences (low, medium, and high). Rice grain yield in Pack Ou was lower at upper and mid points on the toposequences whereas, in Xieng Ngeun, lower yield was observed at the low and upper positions. Further, rice grain yield was higher in continuous rice cropping, particularly in 2-year continuous cropping (1.9 t/ha) in comparison with short (1.2 t/ha) and long fallow periods (1.4 t/ha). Rice varieties with greater seedling vigor that could establish rapidly could help improve crop competitiveness with weeds.

Modified crop and landscape management approaches in the uplands also include rice interplanting, which can also help to manage diseases while at the same time increasing yield. Some of these approaches provide an opportunity for diversification, which can improve productivity and sustainability. This is, however, not suitable as a universal approach for all situations (Leung et al 2003). Results from experiments in China (Zhu et al 2000) show that diversification can be effective and agronomically feasible provided that implementation strategies are compatible with the farmers' cultural practices and that the results are economically attractive. In the long term, the strategy helps preserve farmer-preferred traditional varieties with useful traits such as grain quality and adaptability. In Indonesia, where blast is a major constraint in upland rice production, along with Al toxicity and weed problems, the diversification strategy includes interplanting farmer-preferred traditional varieties and high-yielding blast-resistant improved varieties to manage the disease (Castilla et al 2010, Vera Cruz et al 2009). Traditional upland varieties in Indonesia have high to moderate blast resistance. In contrast, the modern varieties released to farmers succumb to blast within 2–3 years (Suwarno et al 2001). Farmers would like to plant modern varieties that give higher yield to raise their income yet retain traditional varieties for consumption and as insurance against blast epidemics. Interplanting may not only help protect the modern varieties against blast but also help increase productivity per area and sustain the use of farmer-preferred traditional varieties. It was shown that, although interplanting may have a disease-reducing effect, a threshold level of resistance in the susceptible varieties is needed to benefit from the interplanting method (Castilla et al 2010, Vera Cruz et al 2009). Interplanting is, for instance, more efficient when the proportion of resistant varieties is higher and when a moderately susceptible variety instead of a highly susceptible variety is used in the combination. Thus, combinations of improved resistant varieties such as Way Rarem and Batutegi with preferred height, duration, and grain quality have proved acceptable to farmers.

Other options for crop and landscape management approach as a form of diversification in the uplands are intercropping or mixed cropping with rice and relay or crop rotation, and mulching, which could conserve resources, increase yield, and enhance income. In Laos, other crops are grown in the same plot together with rice. These crops are maize, cucumber, pumpkin, taro, cassava, chilies, sesame, smooth loofah, sweet potato, long bean, peanut, eggplant, ginger, sorghum, yambean, pigeonpea, and sun hemp (Roder 2001). Recent work in Laos has evaluated *Stylosanthes* with rice (D. Douangdenh and K. Songyikhangxeuthor, unpublished data). Rice-*Stylosanthes* intercropping showed a significant increase in rice grain yield in 25:75% or 75:25% rice:*Stylosanthes* intercrop compared with a pure rice stand (Table 2). Grain yield of rice with the rice:*Stylosanthes* combination was least at 50:50% probably due to more competition between rice and *Stylosanthes*. The harvest index of rice was greatest in plots of 75:25% rice:*Stylosanthes* and rice alone (Table 2). Rice with a *Stylosanthes* intercrop performed better than rice alone, which may be due to *Stylosanthes'* ability to fix nitrogen in the soil and suppress more competitive weeds. In northeastern India, peanut and soybean were used as an intercrop with upland rice, whereas, in the Churia Hills upland rice system in Nepal, cowpea, maize, and peanut were intercropped with upland rice. Crop rotations with upland rice employed in the western midhill uplands of Nepal include vegetables where irrigation is present in early summer or the summer season while, in the Churia Hills, farmers rotate legumes with upland rice. In Karbi Anglong sloping uplands of India, where shifting agriculture is practiced, farmers use contoured strip cropping with improved varieties of upland rice and an array of multiple crops (ginger, pineapple, mustard, banana, sesame, greengram, forage grass). In northern Vietnam, rice grown in the uplands uses mulching with crop residues for weed suppression and moisture conservation.

Farmers in the uplands often experience a lack of seeds due to low yield, especially after a drought period or severe weather. Seed health is the foundation of a healthy crop (Mew et al 2004), and managing seed health to produce premium-quality seeds and ensuring their availability provides not only food security but also seed security (Vera Cruz et al 2009). Upland farmers tend to prefer traditional varieties with good eating quality, good grain characteristics, and other traits for stress tolerance. Endowed with indigenous knowledge of *in situ* seed preservation of these traditional varieties along with improved varieties and other crops, farmers were encouraged to save their own seeds within the community under the concept of a community seed bank (Manzanilla et al 2011, Vera Cruz et al 2009). Different organizational structures of community seed banks or seed systems have been followed in Nepal, the Philippines, Indonesia, and northern Vietnam. To strengthen their knowledge, farmers learned how to produce premium-quality seeds and properly store them, which empowers them to rely on their own harvests, in the absence of certified seed producers of released varieties, and allows them to share seeds through farmer-to-farmer seed exchanges, including cropping technologies that benefit agricultural productivity sustainably. Such approaches are expected to have a positive impact on landscape management and on crop productivity.

Submergence-prone environments

Rice is the major crop in flood-prone areas of South and Southeast Asia, providing food for millions of subsistence farming families. These areas are subject to either more frequent flash or temporary floods (submergence), longer-term flooding of

Table 2. Rice grain yield, harvest index, tillering ability, and plant height at different proportions of rice-*Stylosanthes* intercrop.

Crop combination	Rice yield (t/ha)	Harvest index	Tiller number	Panicle number	Plant height (cm)[a]	
					MTS	BH
Rice 25% and stylo 75%	2.26	0.25	15	10	89	111
Rice 75% and stylo 25%	1.57	0.32	11	10	89	109
Rice 50% and stylo 50%	1.05	0.26	13	9	87	106
Rice only	0.73	0.30	13	9	89	110
5% LSD, 6 DF	0.41	0.20	4	3	14	15
CV%	15	35	16	15	6.9	6.2
Probability	0.00	0.77	0.24	0.75	0.88	0.68

[a]MTS = maximum tillering stage, BH = before harvest. Unpublished data (D. Douangdenh and K. Songyikhangxeuthor).

20–50 cm (partial/stagnant, semi-deep), deep water of >100 cm (deepwater rice), or very deep water of up to 3 or 4 m (floating rice). Rice productivity in these ecosystems is on average only about 1.5 t/ha because of the lack of high-yielding varieties tolerant of these stresses (Swain et al 2005). The challenges facing rice production in these flood-prone areas are more pressing and complex because of sea-level rise and the probable increase in extreme rainfall events caused by climate change, particularly in coastal areas where rice-based systems predominate. Efforts to improve rice productivity in these areas will ultimately contribute to global efforts to cope with these changes and ease their adverse effects on the food security of rice farmers and consumers.

Our current understanding of the constraints and challenges facing farmers in these areas is rapidly advancing, and prospects for increasing productivity are becoming increasingly visible. As an entry point, narrowing yield gaps in flood-affected areas should commence with developing and deploying resilient high-yielding varieties with submergence tolerance and shorter duration than the existing low-yielding long-duration landraces. Such varieties provide enormous opportunities for proper crop management, more input use, and further adjustments to maximize system productivity and farmers' income. Good agronomic practices targeting proper crop establishment, better survival of flooded plants, and faster recovery thereafter already showed considerable promise in some areas (Ram et al 2009). Soils in these areas are often fertile because of the recurring deposition of silt and organic materials carried in the floodwater. Freshwater resources are sometimes available from surface storage facilities and streams and, in some cases, from renewable underground water resources, providing opportunities for dry-season farming. This provides tremendous opportunities for food security in these areas, as both rice and other crops grown during the dry season are less vulnerable to climate perturbations commonly experienced in the wet season as a consequence of the cycling weather conditions or probable global warming, as witnessed in recent years with increasing incidences of cyclones and coastal storms (Ismail and Tuong 2009).

In the past few decades, significant progress has been made in developing high-yielding rice varieties adapted to rainfed and flood-prone areas (Mackill et al 1993, Neeraja et al 2007, Septiningsih et al 2009). However, research on developing good management strategies has been and is still lagging behind. For example, specific nutrient recommendations have not been developed for flood-prone areas and farmers often abstain from using inputs as a risk-aversion strategy. Also, traditional landraces normally benefit only little from extra inputs, and available modern varieties are often heavily damaged when flooded, resulting in little or no gain from extra inputs. Increasing availability of tolerant varieties provides more opportunities for developing and validating numerous management options that are effective in flood-prone areas (Ella and Ismail 2006, Ram et al 2009). Recommendations are being developed and refined and some of them are already being tested or out-scaled in target areas.

Achieving good crop establishment is a major challenge in flood-prone areas because rice is relatively more sensitive to flooding during germination and early seedling growth. Direct seeding is being practiced in many deepwater areas, and recently it started gaining momentum in flash-flood and other rainfed areas because of its lower cost and operational simplicity, besides other benefits (Pandey et al 2002). Our recent research identified a few landraces that can germinate better in flooded soils (Ismail et al 2009, Angaji et al 2010), and proper seed and seedbed management practices were developed that can further enhance the performance of breeding lines developed from these landraces (Ella et al 2010). For transplanted rice, proper nursery management can significantly enhance crop establishment, survival, and recovery when flooding occurs shortly after transplanting. This can considerably increase grain yield if complete submergence occurs later during the vegetative stage (Ram et al 2009). Such options should be particularly attractive to farmers since they need to apply these options only on the small area occupied by seedbeds. These options include proper nutrient management, the use of organic manure, use of a lower seed density, proper water management, and transplanting of older seedlings when flooding is anticipated early after transplanting (Table 3). High nutrient applications (especially N) should be avoided since they result in vigorous growth and less stored carbohydrate reserves needed for maintenance during submergence (Ella and Ismail 2006). In some flood-prone areas, farmers practice double transplanting 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 seedlings while waiting for the floodwater to recede to levels that can allow transplanting in the main field. Such a system with triple transplanting is practiced in Indonesia and 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 after transplanting in the field (Ram et al 2009).

The application of fertilizer as flooding recedes, when possible, can also contribute to increased productivity (Table 4). The application of nutrients that hasten recovery and increase early tillering can considerably increase yield because these early tillers can be productive. High early tillering also reduces the chances of excessive late tillering, which either considerably extends crop duration or leads to tillers that remain vegetative. Such postflooding management is possible in areas where typical flash floods occur, after the water recedes to levels that make nutrient application possible. Responses to fertilizer, particularly nitrogen, can be observed even if applied within a few days after the water recedes, and a second dose can be applied just before panicle initiation.

In some countries such as Vietnam, Bangladesh, India, and Thailand, dry-season rice became a major crop that transformed farmers' livelihood in flood-prone systems, resulting in substantial improvements in rice production and food security. This has become possible after investing in irrigation and flood control infrastructure as in Vietnam, or through the use of subsurface water by shallow tube wells as in Bangladesh, coupled

Table 3. Effects of nutrient management in the nursery on rice yields in farmers' fields in flood-prone environment of eastern Uttar Pradesh, India, during the wet season of 2007. CNRM: 60, 40, 20 kg of NPK and 10 t of FYM per ha applied at sowing in the nursery.

Village	Genotypes	Survival (%)		Grain yield (t/ha)		Remarks
		Control	CNRM	Control	CNRM[a]	
1	NDR 9730018	–	80	–	5.5	Submergence during early stage
	Swarna-Sub1	30	65	1.8	3.5 (94%)	
2	NDR 9730018	30	85	1.5	5.2 (246%)	Submergence for 2–3 weeks
3	NDR 9930111	60	85	3.2	4.5 (41%)	Submergence twice
4	Swarna-Sub1	100	100	4.8	5.1 (6%)	Submergence two times
	Swarna	100	100	4.6	5.8 (26%)	
5	Swarna-Sub1	35	60	1.5	3.2 (113%)	
	NDR8002	45	75	3.8	4.5 (18%)	
6	Swarna-Sub1	75	92	4.8	5.9 (23%)	Partial submergence
	Swarna	65	80	4.6	5.6 (21%)	

[a]Numbers in parentheses are % increase over untreated control. Unpublished data (P.C. Ram and A.M. Ismail).

Table 4. Grain yield response to nutrients applied 12 days after water recedes. Data are from an on-station trial conducted during the wet season of 2006, Rangpur, Bangladesh.

Postflood nutrients	Grain yield (t/ha)
Control (−NPK)	4.8
NP ($N_{60}P_{30}$)	5.6
NK ($N_{60}K_{20}$)	5.8
NPK ($N_{60}P_{30}K_{20}$)	5.1
5% LSD	0.3

Source: Unpublished data (M. Mazid and A. Ismail).

Table 5. Rice yield equivalent of different cropping sequences. Data are from a trial conducted during the wet season of 2006, Rangpur, Bangladesh.

Cropping sequence	Rice equivalent yield (t/ha)
Direct-seeded BR11/BRRI dhan33-early potato-maize relay or maize	20.2
Direct-seeded BR11/BRRI dhan33-early potato-late boro or BRAUS (double-transplanted rice)	16.9
Direct-seeded BR11/BRRI dhan33-early potato-late boro or BRAUS (single transplanting with older seedlings)	16.8
Direct-seeded BR11/BRRI dhan33-early potato-mungbean	14.0
Direct-seeded BR11-direct-seeded BRRI dhan29 (check)	10.1

Source: Unpublished data (M. Mazid and A. Ismail).

with the availability of short-maturing high-yielding varieties. However, these resources are highly underexploited in some countries, as, for example, in Indonesia, despite the presence of renewable good-quality water at shallow depths. Dry-season rice could provide greater food security because it is less vulnerable to natural hazards, but the system requires initial investment in irrigation, the development of suitable short-maturing varieties, and proper management options. This is also possible only if exercised at the community level to avoid the discouraging damage caused by rats and birds and high disease and insect pressure if just small areas are grown during the dry season. The availability of short-maturing high-yielding varieties, tolerant of prevailing biotic and abiotic stresses, could also provide opportunities for various options of cropping patterns, particularly if combined with direct seeding of rice (Table 5). The choice of nonrice crops in such systems should be carefully considered to ensure that they can fit within the available time window, have good market value, and that farmers have market access.

Salt-affected soils

Salinity and other associated stresses are important constraints to rice production in some soils in humid and subhumid coastal climates as well as in some inlands of Asia (Ismail et al 2007, 2009). Up to 27 million ha are believed to be affected to some extent by salt stress near the coasts of South and Southeast Asia (Ponnamperuma and Bandyopadhya 1980), of which 3.1 million ha are in India, 2.8 million ha in Bangladesh, and 2.1 million ha in Vietnam. The majority of these areas are not currently in use for agricultural production but some are potentially suitable for rice cultivation. Salinity in these areas varies seasonally, being high in the dry season due to capillary rise, and peaking before the onset of rains. Salinity in soil and water then decreases progressively during the monsoon season and is lowest during June to September (Mahata et al 2009). Unlike inland areas, the dynamic nature of salinity on coastal land makes it difficult to conduct long-term soil reclamation. Rice is the most suitable crop for most of these coastal areas because of its ability to flourish in flooded soils, a condition necessary for leaching salts out of the soil.

One of the very likely consequences of global warming is the increase in area and severity of soil salinity, in both coastal and inland ecosystems. In coastal areas, an increase in salinity intrusion has already been witnessed in some of the low-lying deltas, as in southern Bangladesh, Vietnam, and Myanmar (Wassmann et al 2004). These are the consequences of catastrophic storm events, possibly aggravated by a slight increase in sea level and subsiding land surface in many deltas (Syvitski et al 2009). In inland areas, salt deposition is possibly increasing as a consequence of increased evapotranspiration with rising temperatures.

Despite the considerable progress made in developing rice varieties that are tolerant of salt stress, the productivity of salt-affected areas still remains relatively low, at 1–1.5 t/ha (Gregorio et al 2002, Ismail et al 2007, 2009). However, yield in most of these areas can be raised by at least 2 t/ha when validated management and stress mitigation strategies are used together with salt-tolerant varieties (Ponnamperuma 1994). An array of technologies has been developed and found to be effective as amendments and mitigation measures for both short-term (coastal areas) and long-term (inland) reclamation of salt-affected soils (Mahata et al 2009, Singh et al 2010). These technology options include improved agronomic management packages, water harvesting and water management, and soil salinity and fertility management. An example showing the effects of transplanting seedlings of proper age and at closer spacing is shown in Figure 3. The availability of short-maturing salt-tolerant varieties also provides opportunities for crop intensification in areas where freshwater resources are available or could be made available through water harvesting and management of surface-water resources in the dry season. However, in areas where these resources are limited, considerable prospects may still exist through the introduction of short-maturing nonrice crops with lower water requirements than dry-season rice (Table 6). Again, care should be taken when choosing these crops to ensure good market value and benefit to farmers as described above for flood-prone areas. Developing infrastructure that can restrict the intrusion of saline water and enhance drainage such as flood control polders and sluices can help to ease the existing stresses and halt further degradation with global climate change. Improved management of natural resources should also take into account the endogenous knowledge of farmers in coping with these changes and their socioeconomic aspects, in parallel with the development of new concepts and strategies.

Because coastal areas of the tropics, and particularly low-lying deltas where rice is the dominant enterprise, are more vulnerable to any changes in sea level or weather variability,

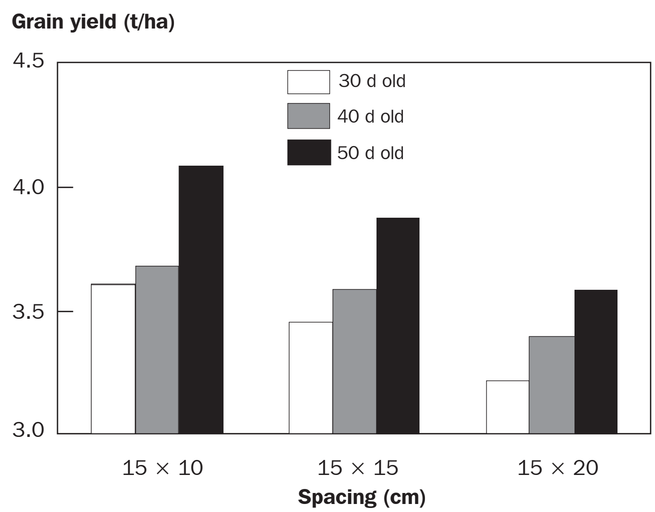

Fig. 3. Grain yield of SR 26B as affected by seedling age at transplanting and spacing in the field. Data are from an experiment conducted in a salt-affected farmer's field in coastal Orissa in the wet season of 2005. $LSD_{0.05}$ = 0.29. (Unpublished data of D.P. Singh and A.M. Ismail.)

Table 6. Effects of rice establishment method on rice and chickpea grain yield in five seasons with varying rainfall in an on-station experiment at Raipur, Chhattisgarh, India. Rice as well as the postrice crop were grown under rainfed conditions without irrigation.

Crop	Establishment method[a]	Years				
		1995-96[b]	1996-97[b]	1998-99[b]	1999-2000[c]	2000-01[d]
		(grain yield in t/ha)				
Rice	DDS dry	6.76	5.71	4.61	4.22	3.12
	DDS moist	5.57	3.99	4.21	3.61	0.82
	DDS biasi	–	–	3.55	2.72	0.68
	T	4.54	3.69	3.25	1.69	0.39
Chickpea	DDS dry	0.82	0.92	1.10	0.62	–
	DDS moist	0.78	0.81	0.96	–	–
	DDS biasi	–	–	0.88	–	–
	T	0.64	0.68	0.69	–	–

[a]Establishment methods were dry direct seeding in lines and dry soil (DDS dry), dry direct seeding in lines and moist soil (DDS moist), dry direct seeding broadcast in moist soil and biasi operation (DDS biasi), and transplanting (T). [b]Good to normal year. [c]Moderate drought year. [d]Severe drought year.

diversifying farmers' options will minimize their vulnerability and risks. However, more information is needed on the extent of exposure to probable threats in order to formulate proper risk management strategies and policies for specific agricultural ecosystems, including climate and flood forecasting and warning. Exploring potentials to increase the value of farm output through intensification and increasing the production of higher value crops with less demand for water and better adaptation to existing stresses can also help uplift farmers' livelihoods making them less vulnerable to any adverse consequences of seasonal or long-term climate perturbations. Further details on some successful management strategies are presented elsewhere in this publication (see Adhya chapter, this publication).

Adjusting cropping systems to cope with climate change: opportunities and challenges

Greater variability in the onset of the monsoon and increased incidence of either drought or high rainfall events, as a result of climate change, augur for greater uncertainty at the farm level. In response, there is a need for rice varieties with greater abiotic stress tolerance for drought or submergence, but also for new options that give farmers greater flexibility to respond to the weather. The availability of technologies in the form of germplasm and CNRM options provides opportunities for intensification and also flexibility in the cropping calendar. Chea et al (2001) described "intensification" as growing more than one crop a year either by growing crops in different seasons or growing more than one crop in a season. Options for rice-based cropping systems in lowlands that are available to farmers are to a large extent governed by the availability of adequate fresh water for crop growth and field operations, such as soil tillage, and intervals when excess water and flooding occur. In these areas, options and decisions are governed by position in the toposequence and resulting water flows and drainage capacities.

"Windows of opportunity" in the weather patterns allow farmers to prepare the land, to establish the crop, and to harvest the crop, but depending on other system characteristics. When only long-duration, photoperiod-sensitive varieties were available, and farmers had to puddle the land and transplant the crop to control weeds, opportunities to intensify were very limited. These are now greater, however, due to the availability of photoperiod-insensitive and short-duration varieties, improved market access for upland crops in some areas, and feasible direct-seeding options through mechanization and herbicides. In Cambodia, for instance, a single rice crop is the most common cropping pattern in most lowland areas and varieties of early, medium, and late duration are grown in upper, medium, and lower fields, respectively (Nesbitt and Phaloeun 1997). Double cropping of rice in lowlands is practiced with either early wet-season direct-sown rice followed by main-season transplanted rice (Fig. 4) or main-season rice followed by a dry-season rice crop. Upland crops are grown either before or after rice. Intensification can improve food security and income, and Sengkea (1998), as cited by Chea et al (2001), showed that growing mung bean before rice where previously no prerice crop had been grown could increase farm income by 9%. In eastern India, Rathore et al (2009) reported that advancing the harvest of rice by dry direct seeding of rice rather than transplanting allowed for an increased chance of a successful harvest of chickpea grown on the residual moisture following rice (Table 6). Similarly, in northwest Bangladesh, Mazid et al (2006) demonstrated that dry direct-seeded rice could give yields similar to those established by conventional transplanting and advanced rice harvest by 7 to 10 days. Earlier harvest reduced the risk of terminal drought in rice and increased the opportunity for establishing a high-value crop such as chickpea (*Cicer arietinum* L.) or potato (*Solanum tuberosum* L.) on residual moisture. In this example, the direct seeding of rice was made possible by either simple tools for line sowing and interrow weeding or the availability of herbicides. Similar examples for important changes in the cropping system in adaptation to the environment and based on new technologies were given above for drought-prone, submergence-prone, and saline environments.

CNRM options to mitigate climate change

Rice fields contribute to global warming in several ways. They are estimated to contribute 10–15% of global methane emissions, and methane is a potent greenhouse gas. The reason is that, in flooded rice fields, organic matter (i.e., rice residues) is decomposed anaerobically, resulting in the formation of carbon dioxide and methane. Growing two or even three rice crops a year shortens the time of aerobic decomposition and increases the amount of crop residues, therefore further increasing methane emissions. In addition, intensive rice cropping generally uses considerable amounts of urea fertilizer, which is partly converted to nitrous oxide, another very potent greenhouse gas. Finally, the still widely practiced field burning of residues contributes to the black carbon (soot) in the atmosphere, which was only recently

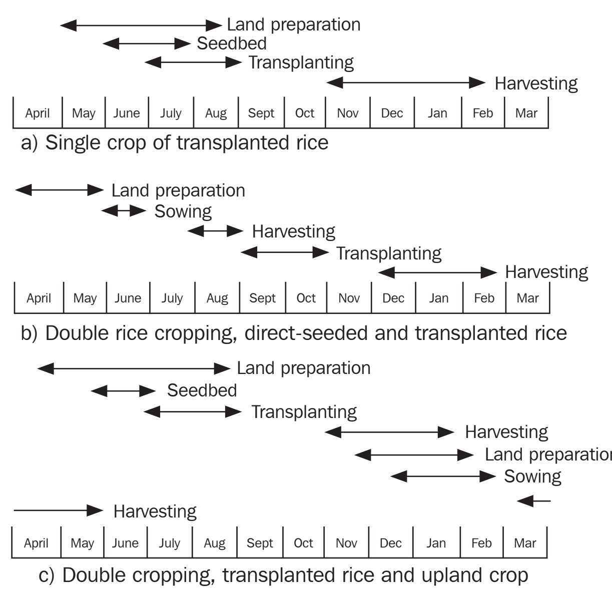

Fig. 4. Rice-based cropping patterns in the lowlands of Cambodia (adapted from Chea et al 2001).

identified as a major contributor to global warming, especially in tropical Asia (Ramanathan and Carmichael 2008).

In traditional rice-livestock systems, still typical for many unfavorable rice production systems, a considerable part of the rice straw is removed as fodder for cattle and only a small part is returned to the fields as manure. Straw is also used for various other purposes such as the construction of houses and other shelters. Usually, only one rice crop is grown, and only a small amount of nitrogen fertilizer is used. Because of the low intensity and limited use of external inputs, straw (and grain) yields are relatively low in these systems. In addition, the fields are not flooded for most of the year, causing most organic matter to be decomposed aerobically to CO_2 only. Therefore, the contribution of greenhouse gases from unfavorable/rainfed systems is limited. However, the effect of intensification in these systems, as targeted by most of the technologies discussed above, is largely unknown and related research is needed. Also, little is known about the contribution of methane from cattle fed with rice residues.

In more modern, intensive systems, less straw is needed for animals because machines take their place. Simultaneously, intensification resulted in more straw, which was then burned because it hindered soil preparation and crop establishment. Burning of rice residues in the field has a range of effects on climate change. It produces considerable amounts of CH_4, comparable to the CH_4 produced when decomposed in anaerobic soils (Miura and Kanno 1997). Second, the soot released into the atmosphere contributes to global warming as mentioned above. But, open field burning is also supposed to transform up to 3% of the initial biomass to black carbon or biochar, remaining on or in the soil. The transformation of organic matter into black carbon greatly reduces its degradability and could therefore contribute to a long-term carbon sink in rice soils (carbon sequestration; Kögel-Knabner et al 2010). But, in recent times, residue burning was banned in most countries because it causes considerable air pollution and negatively affects public health, although it is still practiced in many places. In that situation, farmers are obliged to incorporate large amounts of straw into the soil, resulting in higher CH_4 emissions.

Adjusted water management, residue management, and fertilizer management are therefore the main management elements that can be used to mitigate climate change. Mitigation options should probably be concentrated on intensive irrigated systems because most gains can be made there (Wassmann et al 2000). However, the target could also be to maintain low emissions of greenhouse gases from rainfed systems while simultaneously increasing their productivity. The main objective of methane-reducing management options is to maximize the aerobic decomposition of crop residues in and after the rice season, and/or to reduce the amount of rice residues remaining in the field. This can be achieved, for example, by a change in water management, by soil preparation after the growing season instead of just before the next wet season, or by growing a nonrice crop in the dry season. A different approach would be to remove the residues completely and use them for energy generation, possibly even combined with carbon sequestration through biochar recycling (Haefele et al 2009, Knoblauch et al 2010). This approach would simultaneously reduce the emissions of methane and soot resulting from field burning.

To minimize nitrous oxide emissions, the soil needs to be kept anaerobic for about a week after nitrogen application (Davidson 1991). But, N management should also avoid overfertilization and needs to be tailored to crop demand depending on the site and the crop stage. Slow-release fertilizers could also play a role, provided their value/cost ratio improves.

The change from rice-rice cropping systems to rice-nonrice systems could perhaps reduce greenhouse gas emissions further, but the effect on soil organic carbon could be countereffective because it has been shown that such a change can reduce soil organic matter concentrations significantly (Buresh et al, unpublished). A special case is the change to a cropping sequence that includes a nitrogen-fixing leguminous crop. Such crops can fix considerable amounts of N, which can contribute to increased nitrous oxide emissions (Sharma et al 2005).

These examples show that numerous interaction effects exist, and the consequences of management interventions within and beyond the cropping systems are barely understood. Therefore, considerable research is needed to determine the most promising mitigation options and to more fully comprehend the various effects of system and crop and natural resource management on climate-relevant parameters.

Conclusions

Several of the abiotic stresses that affect rice growth are predicted to increase in importance with the changing climate, and these are already widespread constraints in unfavorable rice environments. These unfavorable rice environments can therefore be used to develop, test, and disseminate adequate rice technologies today for the climate of tomorrow. Successful development of more stress-tolerant rice germplasm for drought, submergence, and salinity is ongoing, and the most advanced products are being disseminated to farmers. In addition, accompanying crop management practices are being developed and substantial benefit can accrue where these are deployed with the germplasm. Further, possibilities exist for large increases in system productivity in these unfavorable environments as has been shown in several cases. Thus, crop and natural resource management for climate-ready rice in unfavorable environments is possible and is the ongoing focus of the Consortium for Unfavorable Rice Environments (CURE). Less importance has been given to climate change mitigation options as the main focus of such options should probably be on intensive irrigated systems where greater gains can be made. However, knowledge of the long-term interaction effects of such mitigation options with cropping system and land management is limited and therefore such approaches need to be analyzed with care.

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Notes

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Photos

Rice landscapes are some of the most productive agricultural areas in Asia but farmers often face constraints of flooding, drought, and salinity. In expected future climates, these constraints may become more serious.

Prolonged wet-season flooding can cause major losses in rice crops.

Varieties are now available that are able to tolerate longer periods of flooding and hence reduce the risks of crop loss.

Salinity can result in low rice yields but, with tolerant varieties and improved management, yields can be greatly improved.

Increased variability in rainfall patterns and reduced rainfall in some areas are likely to result in increased incidence of drought. In these circumstances, drought-tolerant varieties may help reduce farmers' losses.

Crop management may help reduce the effects of drought and increase options for farmers; in India, the transplanted rice (in foreground) was more affected by the early drought than the direct-seeded rice (background).

Rice in upland areas makes a substantial contribution to livelihoods of hill communities. Rice in uplands often suffers from soil, pest, and drought-related constraints, some of which may become more serious with climate change.

The use of better varieties and crop management options can help farmers respond to changing circumstances and improve the returns to their labor.

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