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ADVANCED TECHNOLOGIES OF RICE PRODUCTION FOR COPING WITH CLIMATE CHANGE:

'No regret' options for adaptation and mitigation and their potential uptake

Contents

Producing more with less: exploring farm-based approaches to improve productivity and providing options to farmers in adapting to climate change

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The world needs to produce more grain for food. In addition to almost a billion people who need that, more people will be added to the global population by 2050. But there is no additional land for producing more grain. Even if there were, there is a severe shortage of water. Already, irrigated agriculture in many countries faces severe problems with water. There have been no significant yield improvements in any crop for the last 20 years. This is in spite of the increase in inputs such as improved seeds, fertilizers, pesticides, etc. New approaches that are in the pipeline might take another 15–20 years to be viable, that is, if everything goes according to plan. On top of that, the challenge to produce more good grain will be compounded by climate change, particularly, its added uncertainty for water resources. Therefore, the world needs to concentrate on different approaches to produce more grain while reducing the input costs—seeds, fertilizers, pesticides, and water. Farm-based approaches such as the System of Rice Intensification, Sustainable Sugarcane Initiative, and System of Wheat Intensification, are showing promising results in farmers' fields. These approaches are ecology-friendly and also save large quantities of water if adapted at the river basin level. These farm-based approaches require scientific exploration for further refinement and development. Though these approaches currently show good results in farmers' fields, they have not yet become mainstream research in many agricultural institutions. However, one positive development is that governments, aid agencies, and civil society are investing in these methods, which could certainly help farmers adapt to climate change-induced variations. To exploit the full potential of these promising methods, investments are needed to promote and fine-tune them and do further research to improve the practices. This can be done while investing in other methods that could also provide solutions.

The challenge of producing more

The world needs more grain for food. This has to be achieved even with diminishing arable lands, water scarcity, and rising costs of cultivation. In addition, climate change is adding further complexity. The world population of 6.07 billion in 2000 is projected to grow to 8.13 billion in 2030 and to 8.92 billion in 2050. Average per capita food consumption in developing countries, which rose from 2,110 kcal person^{-1} day^{-1} 30 years ago to 2,650 kcal person^{-1} day^{-1} at present, may rise further to 2,960 kcal person^{-1} day^{-1} in the next 30 years and to 3,070 kcal person^{-1} day^{-1} by 2050. The Food and Agriculture Organization (FAO) and the World Food Program (WFP) reported in their 2009 publication, *The State of Food Insecurity in the World*, that, for the first time since 1970, more than a billion people worldwide (around one-sixth of all humanity) do not have enough food and are hungry and undernourished.

World agriculture has grown at 2.1% to 2.3% per annum in the last four decades. The future may see a drastic decline in the growth of aggregate world production to 1.5% per annum in the next three decades and to 0.9% per annum in the subsequent years to 2050. The cereals sector (sum of wheat, milled rice, and coarse grains) has been in a downward trend for some time now, with growth rate falling from 3.7% per annum in the 1960s to 2.5%, 1.4%, and 1.1% in the subsequent three decades to 2001. An increase in world production by another 1.1 billion t annually will be required by 2050 over the 1.9 billion t of 1999-2001 (or 1 billion t over the 2 billion of 2005). Achieving it should not be taken for granted as land and water resources are now more stretched than in the past and the potential for continued growth of yield is more limited (FAO 2006a). A declining trend in crop yield and an increasing water shortage are apparent in many nations (Rosegrant and Cline 2003).

Since the beginning of the 1960s, the large increase in the demand for food has been met largely by improved agricultural productivity, which required more inputs—fertilizers, pesticides, and improved seeds—and more water for irrigation. Agriculture demanded more and imposing more inputs, putting pressure on water resources and ecosystems and imposing a heavier financial burden on many countries. It is estimated that 70–80% of future increases in crop production in developing countries will have to come from intensification, that is, higher yields (FAO 2006b).

India, having an estimated population of 1.4 billion by 2025, will require 300 million t of grain compared with the approximately 200 million t at present. Little extra land is available and the increase in production will have to come from higher yields, for which there is ample scope (FAO 2006b).

The cost of cultivating food crops has consistently increased owing to the escalating costs of seeds, fertilizers, and labor. With increasing scarcity of labor because of urbanization, sustaining the interest of farmers in crop production itself has become a challenge.

Zeigler et al (2008) listed seven challenges to be addressed in intensive irrigated rice systems. Two of these are (1) exploiting all options for raising the yield potential of rice and (2) closing "yield gaps," increasing yield stability, and improving net returns through improved germplasm with multiple resistance to abiotic and biotic stresses and improved crop management. The projected breakthrough by modifying rice photosynthesis through a C_4 pathway will take millions of dollars and at least 10 to 15 years of dedicated work by a global scientific team (Zeigler et al 2008). So far, the much-publicized strategies surrounding genetically modified (GM) rice have not had much success as seen by the limited spread of the "new plant type" (NPT).

High-input agriculture has clearly reached its limit. Even the more complex solutions in the pipeline require large financial resources, and, if such resources are made available, they require more than 15 years to reach farmers. There is clearly an urgent need to find ways to grow more food with less water and fewer inputs. Farm-based approaches, which used to be at the center of agricultural practices for centuries to improve productivity, need to be explored once again. Farm-based approaches are relatively easy and the results are visible in a short period of time. Some new approaches clearly show promising results in farmers' fields. These methods require further improvement and refinement not just through investments in the field but also through research.

More with more: is it the end of the road?

Current productivity of most smallholder farmers is still far below what is possible and routinely achieved in countries where investment has been appropriate. A marginal increase in smallholder farm productivity worldwide will substantially improve food security. These smallholders, however, may not be able to access the complicated and expensive solutions that are currently in the market or in the pipeline. There are indications in India that these expensive solutions actually lead farmers to commit suicide. This is because of the debts that they incur from purchasing these inputs (Sainath 2009). Clearly, for these smallholders, the "more with more" approach is the end of the road and even the end of their lives. Unsustainable land and water management practices, including deforestation, have also contributed to losses in soil fertility and productivity and disruptions in food production and economic development, especially in the most fragile and marginal environments, where smallholder farmers are the major custodians of natural resources. Unleashing the full potential of smallholder farming is key to the global food security agenda (FAO 2006a).

Globally, there is a large reserve of unused potential farmland. However, only a fraction of this land is realistically available for agricultural expansion as much of it is needed for other purposes, such as forest cover and infrastructure development. In West Asia and North Africa, at least 87% of the suitable land has already been farmed; in South Asia, the corresponding figure is 94%. In many areas, land degradation threatens the productivity of existing farmland and pasture (FAO 2006b). Even if there is land for farming globally, that is not going to solve the problem. Land in countries where people reside has reached its limit. There is no more new farmland in countries where food security is an issue. And, even if it exists, it is still expensive to farm.

From 2001 to 2006, world grain production grew by just 1% per annum, whereas world grain production per capita has continued to fall by –1.2% per annum compared with –0.3% per annum in the 1990s (Uphoff 2006). When the Green Revolution started in China, 1 kg input of N could contribute to 15–20 kg output of additional rice. Today, that increment is only about 5 kg, and it continues to decline (Peng et al 2004).

Under climate change, crops in many regions are prone to environmental stresses that have not been observed before. Many annual crops such as wheat, soybean, and rice have a threshold temperature above which seeds do not form properly. A brief episode of hot temperature (>32–36 °C) can devastate crop yields (University of Reading 2007).

Grain demand in India is estimated to be about 300 million t per annum by 2020, necessitating an increase of about 91 million t from the estimated 209 million t production for 2005-06. Since there is no probability of any further increase in the area under cultivation over the present 142 million ha, much of the desired increase in grain production has to be attained by enhancing productivity per unit area. The productivity of milled rice has to be increased from the present 2,077 kg ha^{-1} to 2,895 kg ha^{-1} by 2020, with an average increase of about 5% per annum. The productivity of wheat has to be increased from the present 2,713 kg ha^{-1} to 3,918 kg ha^{-1}, with an average increase of about 7.5% per annum, whereas the productivity of pulses has to be increased from the present 637 kg ha^{-1} to 1,282 kg ha^{-1}, with an average increase of about 5.3% per annum. On the contrary, the productivity of most crops, except that of wheat, has shown a negative growth rate of 0.72% to 1.84% per annum in 2000-01 and 2002-03. This poses not only a matter of great concern but also a formidable challenge (NAAS 2006).

Grain production in India, following the Green Revolution in 1969-70, yielded 99.5 million t and it nearly doubled by the end of the last century. The highest average annual increase of 6.1% in grain production was recorded during the 1980s: from 110 million t in 1979-80 to 171 million t in 1989-90; but the annual increase in grain production during the 1990s dropped to 1.5%. The fact that fertilizer was the key input in augmenting grain production, next to the availability of seeds of high-yielding crop varieties, is evident from the increase in fertilizer ($N + P_2O_5 + K_2O$) consumption: from 1.98 million t in 1969-70 to 18.07 million t by 1999-2000. Nevertheless, the average annual increase in fertilizer consumption witnessed a declining trend in these three decades—16.5% in the 1970s, 12.04% in the 1980s, and only 5.6% in the 1990s. A simple regression analysis between grain production and fertilizer consumption from 1960-61 to 1999-2000 showed that the partial factor productivity of fertilizers has been continuously declining. This is supported by the fact that farmers in the rice-wheat cropping system belt (especially Punjab, Haryana, and Western Uttar Pradesh) are forced to apply more and more fertilizer to obtain the same crop yield of the preceding years (NAAS 2006).

There was no yield gain in wheat in the last 10 years and plant breeding is strained. An examination of the yield performance of advanced materials in the All-India Coordinated Wheat Improvement Project (AICWIP) multilocation yield trials in timely sown conditions showed that, during the last decade, no entry yielded statistically higher than PBW343 (Nagarajan 2005).

Modern input-intensive rice farming typically involves monocrops, irrigation, and reliance on new seed varieties, synthetic fertilizers, and pesticides. This approach depends on large amounts of water and nonrenewable fossil fuels and has become associated with adverse affects on people's health and the environment over time. Since the dramatic increase in rice production that was achieved in the 1970s and 1980s, yield growth rates in many countries have slowed down. There has been no significant increase in the productivity of major food crops such as rice, wheat, maize, millet, sorghum, and pigeon pea in the past two decades (Figs. 1 and 2).

Increased oil price at nearly $100 per barrel has led to a tremendous stress in government fertilizer subsidies costing, for instance, the Indian government in excess of $1 billion a year. To add to the increased input cost of agriculture, diminishing returns have been noted (Shambu Prasad 2008).

In the next two decades, water scarcity will increase dramatically in many parts of the world. This will have significant social and economic repercussions. Global grain harvests will be threatened, more countries will rely on food imports, and the livelihoods of many people will be threatened (World Economic Forum 2009). Water scarcity will have a significant impact on agriculture. Shortage of water for agricultural production has already become a major problem in some countries. In the world's "rice bowls"—particularly China and India—the scarcity of water is acute, with competing demands on freshwater sources

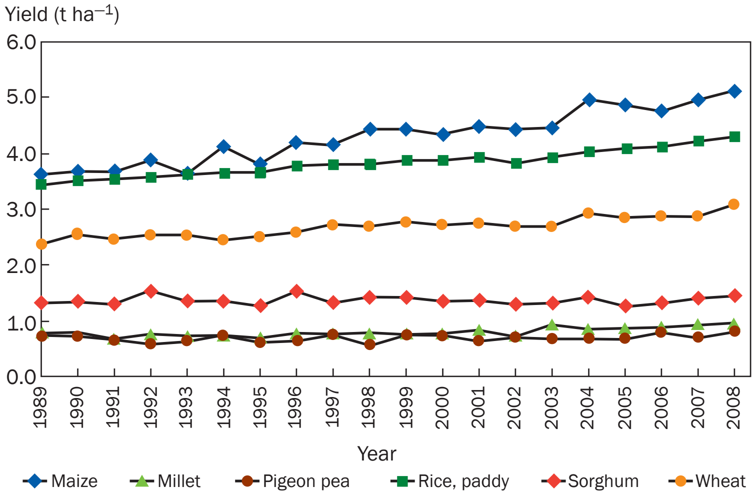

Fig. 1. Trends in the productivity of the world's major crops from 1989 to 2008.

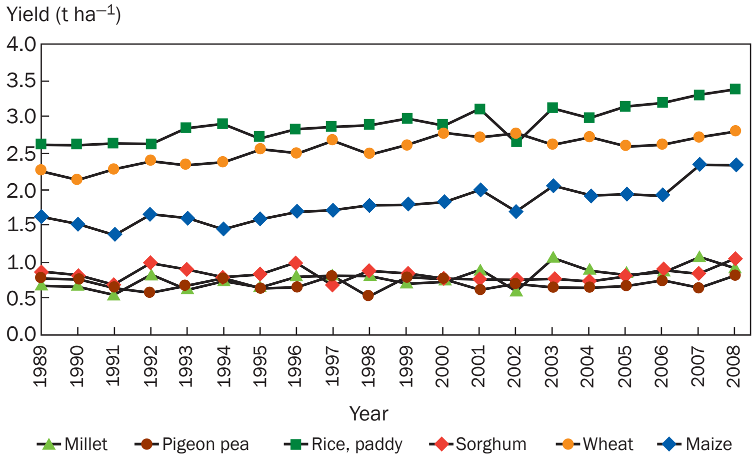

Fig. 2. Trends in the productivity of major crops in India from 1989 to 2008.

triggering conflicts. The declining freshwater availability will have its impact on agriculture in India (Table 1).

Declining per capita freshwater availability in India.

Year	Per capita freshwater availability (m^3)
1951	5,410
1991	2,309
2001	1,902
2025	1,401
2050	1,191

Source: Kumar et al (2005).

More with less: is that possible?

For the last five decades, focus on improving the productivity of crops is based on one thing: more inputs to get more. Farmers were told to use more water, more fertilizers, more (expensive) seeds, and more pesticides in order to produce more. But, giving more to get more has certainly reached its limit. The result is a crisis in the farm sector in many countries. Now, there is a need to think differently. The approach will be to find ways to produce more with less. In the context of climate change and uncertainty in resources such as water, there is a need for a fundamental shift from high-input, high-ecological-footprint agriculture to a more sustainable approach. From an era of high-input agriculture, it is necessary to plunge into low-input agriculture with less use of water, labor, and chemicals. Ensuring food security with this is a big challenge. Historical evidence shows that simple changes in agronomic practices could bring about major impacts on crop yield. Jethro Tull, a famous English farmer (1680-1740), jumped to the conclusion that tillage alone would serve instead of manure. Tull's principle was carried out to better end by Rev. Smith of Lois-Weedon of Northamptonshire. Operating upon a clay soil, Smith produced large wheat crops. His average for many years was 34 bushels instead of 16 bushels, which was the average yield of the locality. He used no manure but simply parceled out his fields in 5-ft-wide strips and grew the crop in drills on alternate strips in successive years. The vacant strips were plowed deeply and frequently, so that through disintegration of the soil, absorption of CO_2, and combined N from the air, plant food enough for the next year's crop was secured (Mukerji 1907).

A century ago, an innovative farmer in Tamil Nadu, India, had the idea of modifying existing agronomic practices in rice cultivation with single seedlings, wider spacing, and some intercultivation operation and reported a yield of 6,004 kg ha^{-1}. This *gaja* method employed interrow spacing of 45 cm and within-row spacing of 30 cm between single plants, resulting in a plant population of only 7–8 plants m^{-2}. Further research into the history of rice cultivation in Tamil Nadu has revealed that, in 1911, several farmers published articles in Tamil language on single-seedling planting (Kulandai Veludaiyar 1911, Anonymous 1911). Scanned copies of these articles in Tamil and their English versions have been published separately (Thiyagarajan and Gujja 2009). It was also found that this single-seedling planting was popularized by the then British government in the Madras presidency.

Vaidyalingam Pillai's reported yield of 6,004 kg grain ha^{-1} with the *gaja* method in Thanjavur District was 2.7 times more than that obtained from the same field the previous year using bunch planting. Yanagisawa (1996) has estimated that the average rice yield in Thanjavur District during 1911 was 1,693 kg paddy ha^{-1}, while the average yield in this district for 1911-15 was 1,492 kg ha^{-1} (Sivasubramanian 1961). It is fascinating to see that such high yields were being obtained by farmers with their own innovations a century ago, when no chemical fertilizers were applied. By 1914, single-seedling planting was being adopted on 40,468 ha (Chadwick 1914).

A major aspect of maximum land use essentially concerns the cultivator himself. It involves improved methods of husbandry, such as manuring, use of better seed, improvement of cultural practices, and control of pests and diseases.

An exciting approach has recently been developed—the System of Rice Intensification (SRI) not only reduces the use of irrigation water but also increases yields significantly and enhances the livelihood of rice farmers (WWF 2007). SRI is perhaps the best example of options available to farmers and nations to promote community-led agricultural growth while managing soil and water resources more sustainably and even enhancing their future productive capacity. As SRI modifies how farmers manage their plants but not the plants themselves, it is compatible with genetic improvement strategies while mitigating the drawbacks associated with monocultures, agrochemicals, and climate change. This makes it a win-win proposition for rural households, countries, and the planet.

SRI was introduced in India in 2000. Today, SRI is known in all rice-growing states in India. It is estimated that as many as 600,000 farmers are growing their rice with all or most of the recommended SRI crop management practices on about 1 million ha distributed across more than 300 of the country's 564 rice-growing districts. This is probably the most rapid uptake of new agricultural practices seen in the country, making SRI a national phenomenon with very limited resources devoted to extension. Both on-farm and on-station evaluations across many states and diverse growing environments have shown clearly that SRI has the potential to improve yield while reducing water use, production costs, and chemical inputs. Available data from SRI experiments across India show an increase in grain yield of up to 68%.

SRI methods are seen to have the following impacts compared with their conventional counterparts (Uphoff and Kassam 2009).

- Depending on current yield, output per hectare is increased usually by 50% or more, with increases of at least 20%, and sometimes 200% or more.
- Since SRI fields are not kept continuously flooded, water requirements are reduced, generally by 25–50%.
- The system does not require purchase of new varieties of seed, chemical fertilizer, or agrochemical inputs,

although commercial inputs can be used with SRI methods.
- The minimal capital costs make SRI methods more accessible to poor farmers, who do not need to borrow money or go into debt.
- Costs of production usually decline by 10–20%. This percentage varies according to the input intensity of farmers' current production.
- With increased output and reduced costs, farmers' net income increases by more than their augmentation of yield.

In a systematically conducted experiment at Hyderabad in the rabi season of 2009-10, SRI crops under organic and inorganic nutrient management resulted in 8.1 and 8.2 t ha^{-1} grain yield with a 12.6% and 13.7% yield increase over the control, respectively. Careful measurement of water use showed that water productivity is higher under SRI and water savings reached 37.5% and 34.2% under SRI-organic and SRI, respectively (Fig. 3).

Experimental evidence is forthcoming on why the rice crop under SRI results in higher yields than under conventional or recommended cultivation practices. Thakur et al (2010) showed that alterations in management practices can induce multiple, significant, and positive changes in phenotype from a given rice genotype. The increase in yield with SRI when compared with that obtained using recommended management practices reached 42% and it was associated with various phenotypic alterations such as longer panicles, more grains $panicle^{-1}$, higher percent of grain filling, increased productivity per plant, deeper and better distributed root systems, higher xylem exudation rates, more open plant architecture with more erect and larger leaves, more light interception, higher leaf chlorophyll content at ripening stage, delayed senescence and greater fluorescence efficiency, higher photosynthesis rate, and lower transpiration. The combination of transplanting single seedlings per hill and the following intermittent irrigation during vegetative growth stage improved root-length density and root activity rate as well as shoot growth and delayed senescence of plants, leading to higher grain yield (Mishra and Salokhe 2010). Zhao et al (2010) reported 26.4% higher yield and significantly higher microbial biomass and microbial biomass nitrogen under SRI when compared with traditional flooding. Yield increased because of the increase in chlorophyll (delayed leaf senescence) and biomass accumulation at later stages.

Farmers see that the main advantages of adopting SRI are considerable savings in seed, water savings of up to 50%, improved soil health, and yield increases of 20–30%. Additional benefits include shorter time to maturity, higher outturn of polished rice when SRI paddy is milled, and resistance to drought and storm damage. The major constraints experienced are lack of trained labor, difficulties in planting young seedlings, water management in low-lying areas, and greater requirements for weeding.

With climate change, increasing variability of rainfall, and the growing competition for water and land, SRI offers a new opportunity for increasing the production value per drop of water and for reducing agricultural water demand, which, in many parts of the world, accounts for the largest share (World Bank Institute 2008).

In India, the significance of SRI is not limited to rice alone. Its core practices are applicable to other crops such as sugarcane. WWF with ICRISAT recently published a detailed manual, *Sustainable Sugarcane Initiative (SSI): improving sugarcane cultivation in India*. Demonstration sites are being put up in five states. The initial results are excellent. Like SRI, SSI could have significant implications for the way that sugarcane is cultivated in the world. Following the principles of SRI, the System of Wheat Intensification (SWI) is gaining popularity in Himachal Pradesh and Uttarakhand states of India. SRI principles of lower seed rate, limited water use, and intercultivation are being applied to crops such as finger millet (*ragi*), mustard, and pigeon pea in various states of India.

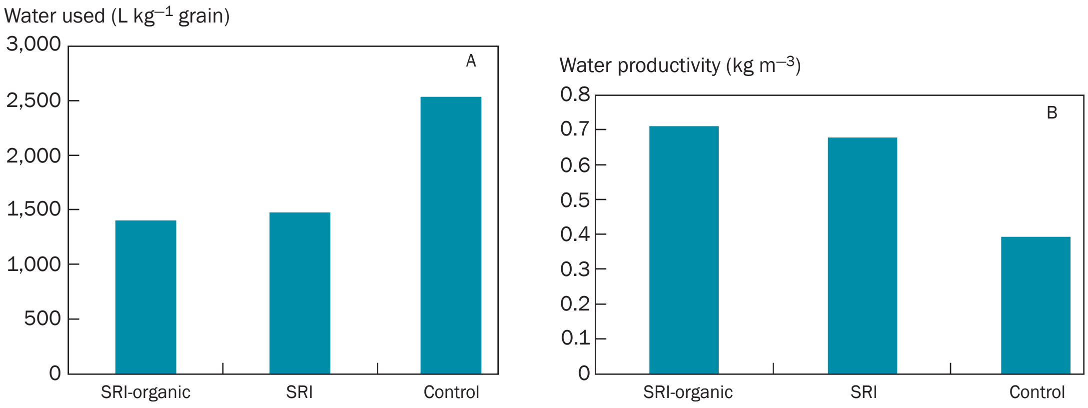

Fig. 3. (A) Water (irrigation and rainfall) used and (B) water productivity in SRI and control rice crops, rabi 2009-10, Hyderabad, India.

Conclusions

The world needs more grain for food. Current methods to improve yield have reached their limits. The "more for more" approach faces a major crisis so there is a need for a major shift in agricultural research. In addition to this, climate change is going to add to the uncertainty. Water shortage is already a major problem that limits rice production and climate change is going to add to the uncertainty of water source in many parts of the rice-growing world. Farm-based methods, which used to be the major focus before high-input agriculture came into the picture, need attention to improve productivity. Already, some practices such as SRI, SSI, and SWI are showing positive results in farmers' fields. These methods have attracted great attention from governments, aid agencies, and civil society organizations. These farm-based approaches highlight the fact that, without investing heavily in new irrigation projects and in modifying existing irrigation systems, water could be effectively used with higher productivity.

Recognizing smart water management and planting practices, farmers in Tamil Nadu have increased rice yields by 30–80% and reduced water use by 30%. World Bank President Robert Zoellick has emphasized that SRI addresses not only food security but also water scarcity, which climate change further aggravates (Hindustan Times 2009). However, these methods still have not been adopted by mainstream research organizations. These methods are very promising, but they require further research and refinement to realize their full potential. The challenge of food security, worsened by the complexity of climate change, could be effectively addressed through farm-based methods, but they need large investments and require immediate attention.

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Notes

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Crop and natural resource management for climate-ready rice in unfavorable environments: coping with adverse conditions and creating opportunities[1]

S.M. Haefele, A.M. Ismail, D.E. Johnson, C. Vera Cruz, and B. Samson

Unfavorable rice environments are defined as environments 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 (rainfed rice), but they also occur in irrigated or partially irrigated systems. The most important rice-based rainfed system in Asia, with respect to area and number of dependent households, is the rainfed lowland ecosystem, which covers about 46 million ha, almost 30% of the total rice area worldwide (Fig. 1). Other rainfed systems with often multiple abiotic limitations are upland rice (about 8.9 million ha in Asia) and deepwater rice (about 3.7 million ha in Asia). 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 affecting rice production are drought (about 23 million ha regularly affected), submergence (about 20 million ha regularly affected), and salinity (about 15 million ha affected).

Thus, weather- and soil-related abiotic stresses are already widespread in many rice-based cropping systems. Climate change, which is predicted to cause higher temperatures, more extreme rainfall events, and a considerable sea-level rise, will most likely make these stresses even more common and severe. To address these existing and potentially growing abiotic stresses in unfavorable environments, the combination of improved germplasm and adjusted crop and natural resource management (CNRM) options is 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 developments, better and more accompanying options for CNRM need to be developed and disseminated together with the new varieties. In this paper, we provide an overview of promising CNRM technologies helping rice farmers to cope with common abiotic stresses, enhancing the tolerance of new rice varieties, and opening new opportunities for intensification and diversification

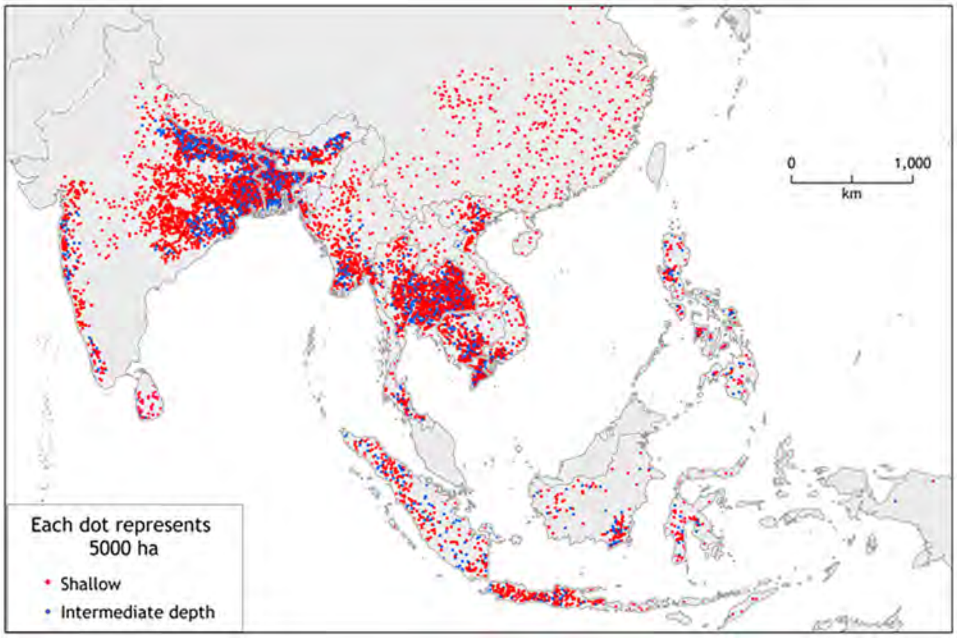

Fig. 1. Distribution of rainfed lowland rice environments across Asia, separated for shallow (0.1–0.3 m usual water depth) and intermediate (0.3–1 m usual water depth) rainfed lowlands). (Modified from Haefele and Hijmans 2007).

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[1] Based on a paper from the CURE workshop on Climate Change, 4 May 2010, Siem Reap, Cambodia.

of cropping systems. We also discuss some CNRM options for climate change mitigation in rice-based systems. This paper aims to provide an overview of the role of rice CNRM in climate change adaptation and mitigation and to highlight the leading role of rice research in unfavorable rice environments for this purpose.

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 very fast from a geological point of view. Therefore, predictions of the effects of climate change are often given for the relatively distant future, say, for 2100 or beyond. But, for developing adjusted CNRM options, mainly changes in the near future are relevant, perhaps within the next 10–20 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 because high temperature can affect rice production at all stages of development, particularly during flowering, when it causes spikelet sterility. It also increases plant respiration, affects photosynthesis, and shortens the grain-filling period, all of which contribute to lower grain yields (Peng et al 2004). Very high temperatures (>33 °C) already occur in some Asian rice-growing regions, but they are mostly limited to the dry season when irrigated rice is grown. Critically high temperatures in the wet season are unusual, and high temperature alone is not very likely to become a major constraint in unfavorable rice areas within the next 20 years. However, even limited temperature stress can be aggravated by drought because the plant loses its ability to cool through transpiration, and the combination of both elements could cause more frequent temperature damage even in rainfed rice (Wassmann et al 2009).

The same authors concluded that, in the near future, changes in precipitation may have a stronger effect 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 rather increase the occurrence of drought. Already, it has been shown that the production of rice, maize, and wheat has declined in many parts of Asia in the past few decades because of 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).

In inland areas, more frequent high-intensity rains will cause more flood events in the lower landscape portions, thereby increasing the occurrence of submergence events. And, coastal and deltaic regions will increasingly be affected by the already occurring sea-level rise. Although the likely average sea-level rise in the coming 20 years is not huge—mean estimates are between 32 and 62 mm for that period based on observed trends in the last century/decade—it is aggravated by an (often rapidly) sinking land surface in most big Asian deltas (Syvitski et al 2009). Both trends together will affect the drainage of inland water; it might cause advancing salinity intrusion in rivers during the dry season and increase the threat from extreme weather events. Therefore, it is assumed 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 adversities of climate change

Drought-prone environments

The biggest area of drought-prone rainfed lowland rice is located in India (13.3 million ha) and Thailand (8.2 million ha), but drought also regularly occurs in the other major rainfed lowland rice regions: 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 (Fig. 1) (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 reduce 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. This approach was practiced in many previously purely rainfed lowland systems and contributed to large productivity increases. Examples are the establishment of large numbers of tubewells in, for example, 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 the drought pattern is relatively stable and of the early-season or late-season type, drought avoidance can be achieved by adjusting the cropping season to the time when water availability by rainfall is best or by reducing the length of the cropping season (and thereby the drought risk). This can be achieved with the help of shorter duration varieties or nonphotoperiod-sensitive varieties. Although these seem obvious options, many rainfed lowlands are still dominated by long-duration, photoperiod-sensitive variety types and no good shorter duration material is available to farmers.

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

Another opportunity to reduce unproductive water losses and moderate drought effects is direct seeding. 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 seed in dry soil could be undertaken before the rains started, while sowing dry seed in moist soil, as practiced with the biasi system, required 112 mm of water on average (Table 2). In comparison, crop establishment by transplanting (including, for that purpose, the necessary soil puddling) and wet plowing in the biasi system required 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 are available yet.

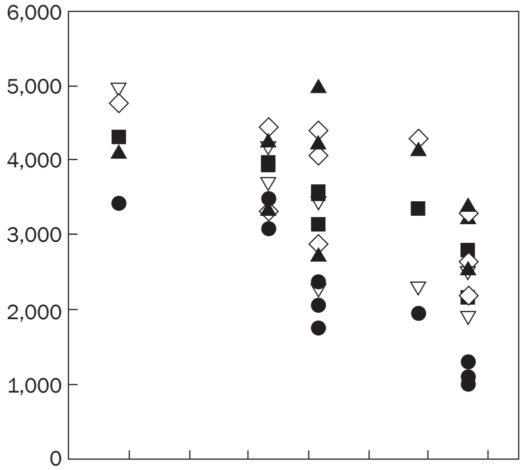

Fig. 2. Grain yield across six sites and different fertilizer treatments but dependent on the mean seasonal field water stress (Pangasinan, Philippines, 2009 wet season). Field water stress levels were scored according to 1 = permanently flooded, 2 = permanently wet soil surface, and 3 = permanently 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 the unfertilized and the fully fertilized treatments.

Table 1. Average time of establishment and corresponding cumulative rainfall in five seasons (1995-2000) depending on 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[b]	Day of year	Cumulative rainfall (mm)
DDS dry	Sowing	159	0
	Establishment[c]	177	131 ± 51
DDS moist	Sowing	180	134 ± 55
	Establishment[c]	195	261 ± 61
DDS biasi[c]	Sowing	174	113 ± 52
	Establishment[c]	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] Establishment refers here to a plant size comparable with seedling size at transplanting. [c] 1998-2000 only.

Other suitable management methods tested in rainfed rice to increase the productive use of water and to reduce unproductive water losses are land leveling and soil improvement. 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, espe-

Table 2. Effects of nutrient management in the nursery on rice yields in farmers' fields in flood-prone environment of eastern Uttar Pradesh, India, 2007 wet season.

Village	Genotypes	Survival (%)		Grain yield (t ha^{-1})[a]		Remarks
		Control	CNRM[b]	Control	CNRM[b]	
1	NDR 9730018	–	80	–	5.5	Submerged during early stage
	Swarna-Sub1	30	65	1.8	3.5 (94%)	
2	NDR 9730018	30	85	1.5	5.2 (246%)	Submerged for 2–3 wk
3	NDR 9930111	60	85	3.2	4.5 (41%)	Submerged twice
4	Swarna-Sub1	100	100	4.8	5.1 (06%)	Submerged twice
	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. [b] CNRM: 60-40-20 kg NPK ha^{-1} and 10 t of farmyard manure ha^{-1} applied at sowing in the nursery. (P.C. Ram and A.M. Ismail, unpublished data).

cially on coarse-textured soils. Where at least partial irrigation is possible, water-saving irrigation techniques such as alternate wetting and drying, saturated soil culture, and aerobic rice are available options to make best use of scarce water resources (Bouman 2007).

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 20–50 cm (partial/stagnant, semideep), 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 only about 1.5 t ha^{-1} 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 becoming more complex because of the continuous sea-level rise and the probable increase in extreme rainfall events caused by ongoing 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 for coping 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 begin with developing and deploying resilient, high-yielding varieties with submergence tolerance and shorter duration than the existing low-yielding, long-duration landraces. These varieties will then provide great 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 2010). 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 2010).

In the past few decades, significant progress was 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 a little from extra inputs, and available modern varieties were often heavily damaged when flooded, resulting in little or no gain from extra inputs. Increasing the availability of tolerant varieties provides more opportunities for developing and validating numerous management options effective in flood-prone areas (Ella and Ismail 2006, Ram et al 2010). Recommendations are being developed and refined and some of them are already being tested or outscaled in target areas.

Proper 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 it has gained momentum in flash-flood and other rainfed areas because of its lower cost and operational simplicity, besides the 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 obtained 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 2010). Such options should be particularly attractive to farmers since they need to apply them only on the small area occupied by seedbeds. These options include proper nutrient management, use of organic manure, use of lower seed density, proper water management, and transplanting of older seedlings when flooding is anticipated early after transplanting (Table 2). High nutrient application (especially N) should be avoided since it results 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 (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., photoperiod-sensitive varieties seem to be better adapted) or proper management of seedlings in nurseries or after transplanting in the field (Ram et al 2010).

Postsubmergence nutrient management, when possible, can also contribute to increased productivity (Table 3). 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 post-flooding management is possible in areas where typical flash floods occur, after the water recedes to levels that make nutrient application possible. Responses to fertilizers, particularly N, can be observed, even if applied within a few days after the water recedes, and a second

Table 3. Grain yield response to nutrients applied 12 d after water recedes. Data are from an on-station trial conducted during the wet season of 2006, Rangpur, Bangladesh.

Postflood nutrient	Grain yield (t ha^{-1})
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

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

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 tubewells, as in Bangladesh. However, these resources are highly underexploited in some countries, as in Indonesia, in spite of 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, 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 could also provide opportunities for various options of cropping patterns, particularly if combined with direct seeding of rice (Table 4). However, the choice of nonrice crops in such systems should be carefully considered to ensure that they can fit within the available time window, that they have good market value, and that farmers have market access.

Salt-affected soils

Table 4. Rice yield equivalent of different cropping sequences. Data are from trials conducted during the wet season of 2006, Rangpur, Bangladesh.

Cropping sequence	Rice equivalent yield (t ha^{-1})
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

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

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 at the coasts of South and Southeast Asia (Ponnamperuma and Bandyopadhya 1980), of which 3.1 million ha are in India, 2.8 million ha are in Bangladesh, and 2.1 million ha are in Vietnam. The majority of these areas are not currently in use for agriculture, 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 levels in soil and water then decrease progressively during the monsoon season and are lowest from June to September (Mahata et al 2009). Unlike in the inlands, the dynamic nature of salinity in coastal areas 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). This is the consequence of catastrophic storm events, possibly aggravated by the slight increase in sea levels and the 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 considerable progress made in developing rice varieties that are tolerant of salt stress, productivity of salt-affected areas still remains relatively low at 1–1.5 t ha^{-1} (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^{-1} 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 technologies include improved agronomic management packages, water harvesting and water management, and soil salinity and fertility management. An example showing the effects of transplanting seedlings with 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 less water requirements than dry-season rice (Table 5). 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 the infrastructure that

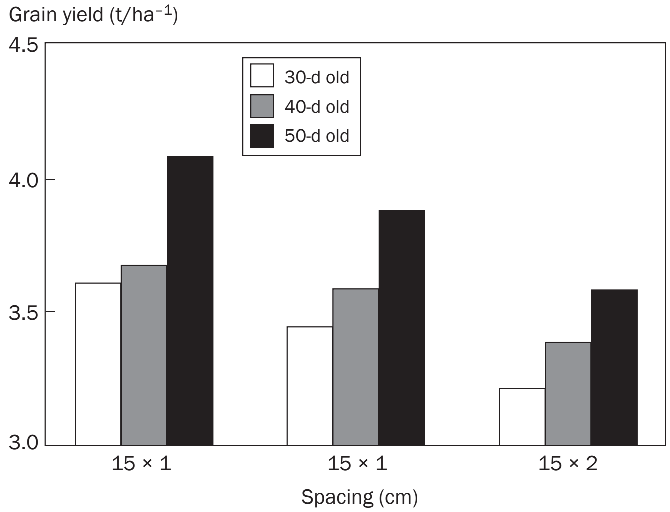

Fig. 3. Grain yield of SR 26B as affected by seedling age at transplanting and spacing in the field. Data are from an experiment conducted in a salt-affected farmer's field in coastal Orissa in the wet season of 2005. $LSD_{0.05}$ = 0.29. (unpublished data of D.P. Singh and A.M. Ismail).

can restrict intrusion of saline water and enhance drainage such as flood control polders and sluices can help ease the existing stresses and halt further degradation with global climate change. Improved management of natural resources should also take into account the indigenous 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, particularly the low-lying deltas where rice is the dominant enterprise, are more vulnerable to any changes in sea-level rise or weather variability, 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 volume.

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

Greater variability in the onset of the monsoon, as a result of climate change, and increased incidence of either drought or high-rainfall events augur for greater uncertainty at the farm level. In response, there is a need for rice varieties with greater tolerance of abiotic stress (e.g., 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 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 there is excess water and flooding. In these areas, options and decisions are governed by position in the toposequence and resulting water flows and drainage capacities.

"Windows of opportunity" in weather patterns allow farmers to prepare the land, establish the crop, and harvest the crop, depending on other system characteristics. When only

Table 5. Effects of rice establishment method on rice and chickpea grain yield (in t ha^{-1}) in five seasons with varying rainfall in an on-station experiment at Raipur, Chhattisgarh, India. Rice as well as the post rice crop were grown under rainfed conditions without irrigation.

Crop	Establishment method[a]	Year				
		1995-96[b]	1996-97[b]	1998-99[b]	1999-2000[c]	2000-01[d]
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	NE
	DDS moist	0.78	0.81	0.96	NE[e]	NE
	DDS biasi	–	–	0.88	NE	NE
	T	0.64	0.68	0.69	NE	NE

[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. [e] NE=not established.

long-duration, photoperiod-sensitive varieties are available, and farmers have to puddle the land and transplant the crop to control weeds, opportunities to intensify are 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 on the upper, medium, and lower fields, respectively (Nesbitt and Phaloeun 1997). Double cropping of rice in the 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 mungbean before rice where previously no prerice crop had been grown could increase farm income by 9%. In eastern India, Rathore et al (2010) reported that advancing the harvest of rice by dry direct seeding of rice rather than transplanting allowed for increased chance of a successful harvest of chickpea (*Cicer arietinum* L.) grown on residual moisture following rice (Table 5). Similarly in northwestern Bangladesh, Mazid et al (2006) demonstrated that dry direct-seeded rice could give yields similar to those of conventional transplanting and could advance the rice harvest by 7–10 days. Earlier harvest reduced the risk of terminal drought in rice and increased the chances of establishing a high-value crop such as chickpea or potato (*Solanum tuberosum* L.) on residual moisture. In this example, direct seeding of rice was made possible by either simple tools for line sowing and interrow weeding or herbicides. Similar examples of important changes in the cropping system as an adaptation to the environment and on the basis of new technologies were given 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

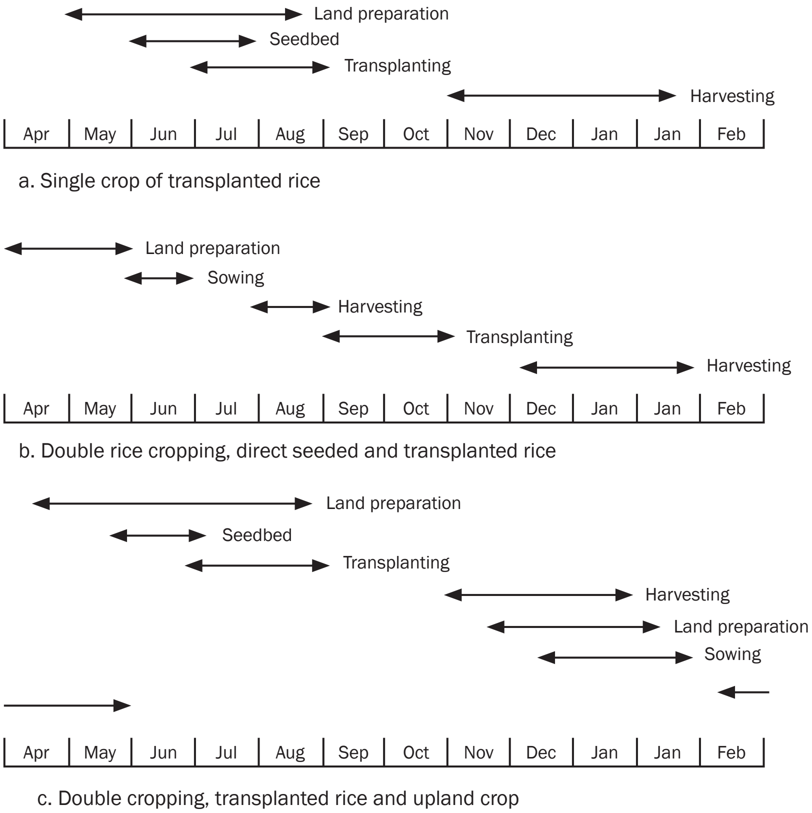

Fig. 4. Rice-based cropping patterns in the lowlands of Cambodia (adapted from Chea et al 2001).

black carbon (soot) in the atmosphere, which was only recently 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 construction of houses and other shelters. Usually, only one rice crop is grown, and only a little N 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 into 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 results in more straw being burned because it hinders 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 methane comparable with that produced during decomposition in anaerobic soils (Miura and Kanno 1997). Second, as mentioned above, the soot released into the atmosphere contributes to global warming. But open-field burning is also supposed to transform up to 3% of the initial biomass into black carbon or biochar, remaining on/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 methane emissions.

Adjusted water, residue, and fertilizer management is therefore the main element 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 emission 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 N application (Davidson 1991). But N management should also avoid overfertilization and should be tailored to crop demand, depending on the site and the crop stage. Slow-release fertilizers could also play a role, provided that 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 counterefective 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 an N_2-fixing leguminous crop. Such crops can fix considerable amounts of N_2 that can contribute to increased nitrous oxide emissions (Sharma et al 2005).

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

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Temperature effects on rice: significance and possible adaptation

S.V.K. Jagadish, K. Sumfleth, G. Howell, E. Redoña, R. Wassmann, and S. Heuer

The increase in both frequency and intensity of high temperature, along with its large variability, is emerging as a potential threat to the sustainability of rice production. Recent data reveal an abnormal increase in diurnal temperatures, with night temperature increasing at a much faster rate than day temperature. Experimental evidence indicates the importance of assessing the effects of day and night temperature separately rather than those of daily mean temperature alone. In response to high day temperature, some rice genotypes exhibit efficient adaptive mechanisms—early-morning flowering to escape high temperature during later hours of the morning or early noon and high-temperature avoidance through efficient transpiration cooling to maintain canopy/tissue temperature below a critical level. However, rice, in general, may not possess such mechanisms to adapt to increasing night temperature and this could result in a greater yield reduction with a slight increase in night temperature compared with high day temperature. Studies focusing on high day temperature and, more recently, on night temperature have increased, but, for a more comprehensive assessment of the problem, controlled environmental studies should be complemented with studies under field conditions, using standardized phenotyping protocols that take interacting variables (e.g., relative humidity, radiation) into account. This paper focuses on the differential response of rice to high day and high night temperatures, the contribution of different climatic variables to rice productivity under field conditions, and the progress made at the International Rice Research Institute in developing high-temperature–tolerant rice varieties using both genetic and molecular approaches.

Rice with relatively higher tolerance at the vegetative stage is extremely sensitive to high temperature during the reproductive stage, particularly at flowering (Prasad et al 2006; Yoshida et al 1981; Jagadish et al 2007, 2008, 2010a,b). Spatial analysis using cropping pattern data from the *Rice almanac* (Maclean et al 2002) showed susceptible stages of rice (i.e., flowering and early grain filling) coinciding with high-temperature conditions in Bangladesh, eastern India, southern Myanmar, and northern Thailand (Wassmann et al 2009b). Although the global mean temperature could increase by 2.0–4.5 °C by the end of this century, it has been predicted that minimum night temperature will increase at a much faster rate than maximum day temperature (IPCC 2007). For example, during 1979-2003, annual mean day temperature increased by 0.35 °C and mean night temperature increased by 1.13 °C in the Philippines (Peng et al 2004). Rice, with its widely diverse genetic traits—early-morning flowering (EMF) to escape higher temperature during the later hours of the morning (Ishimaru et al 2010) and high-temperature avoidance through transpiration cooling (Weerakoon et al 2008)—is better equipped to withstand high day temperature, provided that sufficient water is available. However, the limited stomatal activity at night makes rice extremely vulnerable to rapidly increasing night temperature. Considering the current and predicted rates of increase in night temperature, the negative impact on rice production is likely to be felt on a much wider scale, with significant yield losses. High night temperatures are commonly associated with increased respiration rates, leading to a decline in yield (Mohammed and Tarpley 2009b). However, a certain degree of overlap of physiological processes (e.g., reduced pollination, number of pollen germinated on the stigma, and increased spikelet sterility) under both high day and night temperatures has been documented (Jagadish et al 2010b, Mohammed and Tarpley 2009a).

Further, increases in CO_2 concentration and other climatic factors such as solar radiation and relative humidity influence the degree to which high temperature affects rice productivity. The contribution of these variables to yield variation has received less attention. Using climate information from different rice-growing regions in Pakistan, Australia and India (hot and dry conditions), and Bangladesh and the Philippines (moderately hot and highly humid), the importance of these variables in drawing conclusions about temperature-related effects is highlighted. Additionally, with the gradual shift from intensive irrigated systems, in which standing water creates a cooler microclimate, future water-saving technologies (e.g., alternate wetting and drying, aerobic rice, and direct-seeded rice) could be more vulnerable to the adverse effects of high temperatures. There is thus an urgent need to address high-temperature–induced yield losses in rice under current climatic conditions and more so in the face of a changing climate scenario.

Adapting to high day and night temperature

Diurnal temperature change can significantly affect rice production. Day temperatures beyond the critical level can adversely affect photosynthesis, by changing the structural organization of thylakoids and disrupting photosynthetic system II (Karim et al 1997, Zhang et al 2005). This will, in turn, increase the generation of reactive oxygen species, leading to the loss of cell membrane integrity, cell content leakage, and, ultimately, death of cells (Schoffl et al 1999, Howarth 2005). Rice cultivated under a flooded paddy system is generally not exposed to this level of high-temperature stress. The buffering capacity of standing water, along with efficient transpiration cooling, creates a microclimate with lower temperature, even when ambient air temperature is very high. Modern rice cultivars, with their long, erect flag leaves, can provide additional cooling and shade, whereas traditional varieties, with their short flag leaves and long internodes, have their panicles exposed to high ambient air temperatures, making them more vulnerable (Wassmann et al 2009a). Empirical studies under field conditions show that high day temperature had no significant negative effects on grain yield (Peng et al 2004, Welch et al 2010, Nagarajan et al 2010). In all three studies, the flowering stage was exposed to maximum temperatures of 32−36 °C, which were close to the critical threshold of 35 °C (Yoshida et al 1981). But, with transpiration cooling in place under sufficient water supply, high day temperatures would have had little impact on rice yield. Moreover, studies conducted in controlled environments reveal that the effect of high temperature is closely related to ambient relative humidity (RH)─hence, the level of transpirational cooling is determined by vapor pressure deficit rather than by high temperature per se. Abeysiriwardena et al (2002) recorded a 1.5 °C increase in spikelet temperature by increasing RH from 55–60% to 85–90% at a constant temperature regime of 35/30 °C. Moreover, Weerakoon et al (2008), using a combination of high temperature (32–36 °C) with low (60%) and high (85%) RH, recorded high spikelet sterility with simultaneous increases in temperature and RH. These studies suggest that the reduction in spikelet temperature at lower RH indicates avoidance and that the variety, which maintained higher spikelet fertility under high temperature and high RH (low VPD), is truly high-temperature-tolerant.

The predicted doubling of CO_2 concentration by the end of this century could significantly increase photosynthesis, growth, development, and yield of rice (Ziska and Teramura 1992, Baker et al 1990, Ziska et al 1996). With elevated CO_2, crops have been shown to maintain high productivity under a wide range of stress conditions, including shortage of water (Prior and Rogers 1995) and nutrients (Hocking and Meyer 1991) and high concentrations of tropospheric ozone (Allen 1990). However, a negative interaction between elevated CO_2 and high temperature has been reported (Matsui et al 1997). In this study, elevated CO_2 resulted in higher stomatal closure, reducing transpiration cooling and thereby increasing spikelet sterility, even when sufficient water was available. Moreover, the critical high temperature threshold that induces spikelet sterility was reduced by 1 °C with a simultaneous increase in CO_2 and temperature (Matsui et al 1997).

The 2007 heat wave in Pakistan coincided with the sensitive flowering stage of IR6, a widely grown variety, resulting in a 30% yield reduction. In the same year, hybrids recorded a yield decline of 70% under fully irrigated conditions (Dr. Mari, RRI, Dokri, personal communication). These examples show that adaptive mechanisms, such as transpirational cooling, are effective to a certain point. Beyond this, short episodes of extremely high temperature at the sensitive developmental stage can have a devastating effect, even under irrigated systems. Moreover, with the increasing demand for fresh water, different water-saving techniques (e.g., alternate wetting and drying, aerobic rice, direct seeding) are now being explored. With the removal of the thermo-protective water layer covering the soil, both soil and crop canopy/tissue temperatures are likely to increase as shown by thermal-imaging studies (Munns et al 2010). Detailed studies are needed to quantify the potential negative effects of high temperature on water-saving systems and to enhance system adaptability to future climatic conditions.

Although there is substantial information on the effect of high day temperature on rice spikelet fertility/seed set under controlled-environment conditions, there are no reports, to our knowledge, on systematic analysis of high-temperature effects in vulnerable regions. Extreme temperature events during sensitive developmental stages, which negatively affect rice yields in China and Japan, do not follow a pattern consistent enough to be the basis for developing effective screening protocols. However, regions such as Pakistan and northern and southern India have hot, extended summers suitable for screening rice germplasm to identify prospective heat tolerance donors that can be used by breeders to develop high-temperature–tolerant rice varieties. At IRRI, through the Cereal Systems Initiative for South Asia, we have initiated such trials in India, Pakistan, and Bangladesh.

High night temperature (HNT) has recently become a major rice research area. A very narrow critical range of 2−3 °C has been shown to result in drastic grain yield reduction in the tropics (Nagarajan et al 2010) and subtropics (Peng et al 2004) (Fig. 1). Although the reduced yield caused by HNT may be attributed to higher respiration rates (Mohammed and Tarpley 2009b), the percentage yield decline was much higher than the percentage increase in respiration rate (Peng et al 2004). Similar yield reductions in maize, wheat, and soybean under increasing night temperatures could not be fully explained solely by higher respiration (Peters et al 1971). The effect of increased night temperature on crop duration has not been investigated to date. Additionally, the avoidance mechanism through transpiration is limited at night as stomatal activity is at its peak during the day and minimal at night (Rogers et al 2009). Moreover, a diverse genetic base has been tested to identify high-day-temperature–tolerant rice varieties (Prasad et al 2006, Jagadish et al 2008, Matsui et al 2001), while a limited set of genotypes has

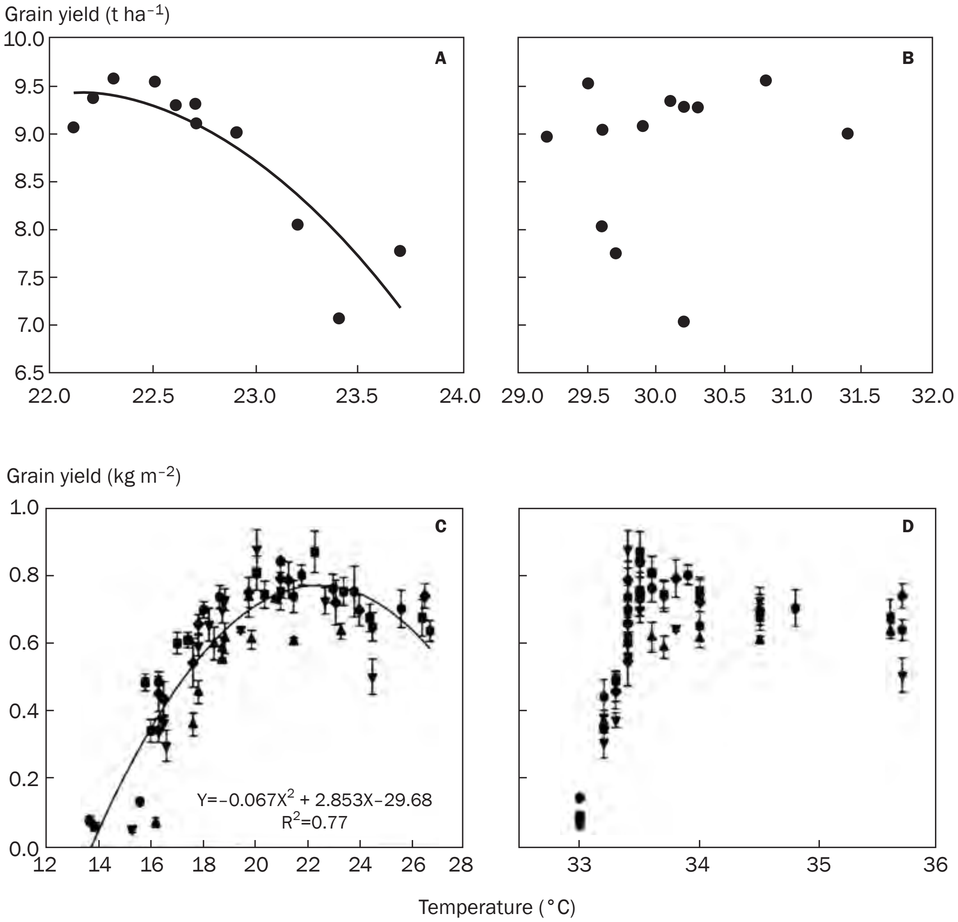

Fig. 1. Relationship between rice-yield and growing-season mean minimum (A,B) and maximum (C,D) temperature. Growing-season mean maximum and minimum temperatures were calculated from daily values for the entire growing season from transplanting to harvest.
Adapted from Peng et al 2004 and Nagarajan et al 2010.

been tested under HNT conditions (Peng et al 2004; Nagarajan et al 2010; Cheng et al 2008, 2009; Mohammed and Tarpley 2009 a,b, 2010). Further studies on a wider range of genotypes are needed to explain the genetic diversity in HNT tolerance and to confirm the critical temperature threshold identified.

A comparison of the effects of HNT on grain yield under field and controlled conditions revealed a significant decline beyond 22 °C in the field, while the same could be achieved only at 32 °C under controlled environments (Peng et al 2004). Moreover, HNT under field conditions also reduced biomass by 10% for a 1 °C rise in critical level (from 22 to 23 °C) (Peng et al 2004, Nagarajan et al 2010). Meanwhile, studies conducted under controlled conditions, even at 32 °C, recorded higher total biomass as well as higher stem and leaf dry matter accumulation (Kanno et al 2009, Mohammed and Tarpley 2009b, Cheng et al 2009). These studies suggest that other factors also affect grain yield in the field and further research must be done to analyze these in detail. When HNT coincides with critical developmental stages such as flowering, there would be improper pollination and a reduction in the number of pollen germinated on the stigma, which ultimately would lead to spikelet sterility (Mohammed and Tarpley 2009a). These effects are similar to those caused by high day temperatures, indicating that increased day or night temperature at the reproductive stage could lead to increased sterility. Therefore, the effects on basic physiological processes (such as photosynthesis and respiration) and on other vegetative parameters recorded in response to high day/night temperature under controlled conditions have to be interpreted with caution; the effects seen during the reproductive stage across different scales seem to be in agreement.

Neglected climatic variables

The observed differences in the effect of high day temperature between experiments might largely be attributed to climatic variables such as RH, radiation, and wind modifying the effects of high temperature under natural conditions. These climatic variables, though very important, often receive little attention. For instance, the extent to which rice can fully use its ability to reduce canopy temperature under high ambient air temperature by transpirational cooling greatly depends on the RH—i.e., thevapor pressure deficit between the air and the tissue. When one compares a hot and dry location (Jakobabad, Pakistan) with a hot and humid site (Jessore, Bangladesh), the importance of RH and temperature interaction becomes evident (Fig. 2). In March, the eastern part of the Indo-Gangetic Plain has maximum day-temperature values ranging between 30 and 34 °C, with a high RH of 40–70% (this coincides with the high-temperature–sensitive flowering and early grain-filling stages of the dry-season crop [called boro in Bangladesh]). In September, when the rice crop is at a developmental stage similar to that in Bangladesh, the climate in Pakistan is characterized by high temperature (33–36 °C) and very low humidity (10–30%). Differences in RH will greatly affect the ability of the plants to employ evapotranspirational cooling to protect themselves from high-temperature damage.

The second critical factor influencing yield is radiation. Although radiation is a component in most climate models, the empirical data used to predict future high-temperature effects on rice are mainly derived from studies conducted in controlled environments, where the amount of light provided in most cases is significantly low. Grain yield under field conditions was found to linearly increase up to 21 MJ m^{-2} (Peng et al 2004, Nagarajan et al 2010) (Fig. 3). The recently observed significant reduction in yield of IR72 under IRRI's long-term trials in fully flooded conditions could possibly be explained by declining radiation. Climatic conditions, for example, light intensity, may be different, which may alter the effect of high day/night temperatures. Caution must be taken in using data to predict temperature effects on future climate. Moreover, a recent report has shown a substantial decrease in visibility across South and East Asia, South America, Australia, and Africa, resulting in global dimming over land (Wang et al 2009). Studies to quantify the effect of radiation and temperature interaction under field conditions are worth doing.

Wind speed, in combination with dry air conditions under fully irrigated conditions, facilitates rice cultivation at temperatures above 40 °C without any yield penalty. For instance, in Australia, Matsui et al (2007) recorded a reduction in canopy temperature by as much as 6.8 °C with the combination of hot and dry air, strong wind, and sufficient water, allowing rice production without reducing yields. Considering the local climate at target sites vulnerable to high temperature will be essential in dissecting the effects of different climatic parameters. Thisknowledge will help in the formulation of clear strategies to address yield losses due to increasing temperatures and to initiate breeding programs to develop high-temperature–tolerant rice for hot-humid and hot-dry regions.

Approaches to overcome the problem of high temperatures

IRRI is trying two approaches to mitigate the effects of high day temperatures: escape and tolerance.

Escape from high temperature. More than 4,000 *Oryza sativa* indica accessions were field-tested at IRRI to evaluate the use of the EMF trait as a strategy to overcome the effect of high temperatures during the later hours of the morning. From this screening, a few *O. sativa* accessions possessing this trait were identified. Screening of wild rice accessions at IRRI has reconfirmed EMF in *O. minuta* and *O. officinalis* (Sheehy et al 2007). Recently, Ishimaru et al (2010) successfully introgressed the EMF trait from *O. officinalis* into modern variety Koshihikari. The authors showed that the EMF-introgression line started and completed flowering a few hours before the wild-type Koshihikari. This shift in flowering time toward the cooler early morning resulted in a significantly lower heat-induced spikelet sterility compared with that of the wild type. When exposed to high temperatures during flowering, the EMF line was equally

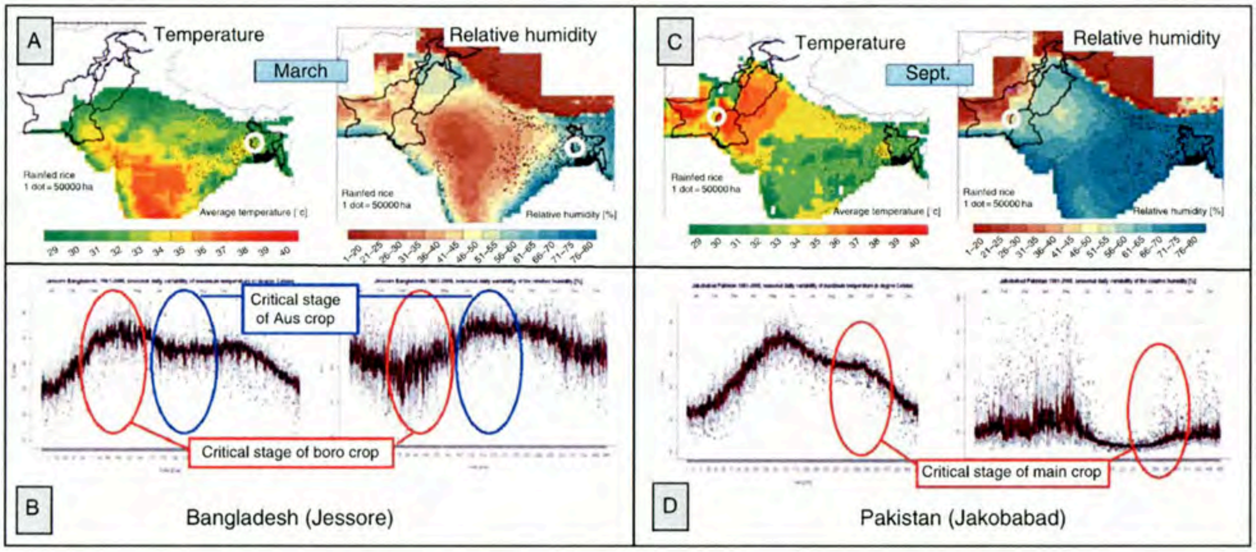

Fig. 2. Temperature and relative humility in South Asia in March (A) and September (C) as well as annual course of temperature and relative humidity in Bangladesh (B) and Pakistan (D). Encircled regions in B and D depict critical stages for the rice plant.
Data source: The National Climatic Data Center (NCDC), Mitchell and Jones, 2005, Huke and Huke, 1977.
Adapted from Wassmann et al (2009a).

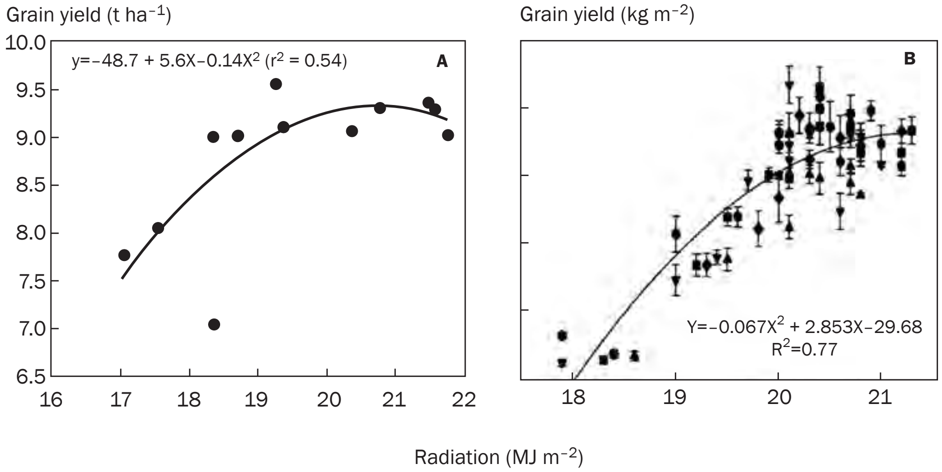

Fig. 3. Relationship between rice-yield and growing-season mean radiation. Growing-season radiation levels were calculated from daily values for the entire growing season from transplanting to harvest.
Adapted from Peng et al (2004) (A) and Nagarajan et al (2010) (B)

sensitive as the wild type, indicating that the mechanisms for escape and tolerance are different and that EMF could provide considerable protection to rice plants at the flowering stage. However, the EMF trait can be strongly influenced by environmental conditions such as light, RH, and temperature (Kobayashi et al 2009). It will now be important to further validate these lines in multilocation trials to determine the stability of the trait and to study the effects of climatic variables.

Heat tolerance. Using a diverse set of genotypes, aus-type variety N22 was identified as an ideal donor of the high-temperature tolerance gene at flowering stage (Yoshida et al 1981, Prasad et al 2006, Jagadish et al 2008). Nearly 25 different genotypes, nominated by breeders from across the world, were tested under stringent conditions (39 °C and 75% RH) at IRRI. N22 maintained its higher tolerance compared with the other nominated entries at IRRI; it performed similarly at the University of Reading, UK, showing that the tolerance trait in N22 was highly stable. However, some of the entries mentioned by the breeders may not be as tolerant as N22, but they may possess effective adaptive mechanisms to help them survive under extreme high-temperature conditions. At IRRI, multiple biparental mapping populations involving the donor parent N22 have been initiated and some advanced breeding lines are now under field trials in India, Pakistan, Iran, and Bangladesh.

Quantitative trait loci (QTLs) for high-temperature tolerance during anthesis have recently been identified from a random inbred population obtained from a cross between Bala (moderately tolerant of high temperatures) and Azucena (Jagadish et al 2010b). We are in the process of validating the identified QTLs using N22-based mapping populations to identify stable QTLs that account for the large phenotypic variation across different genetic backgrounds. On the other hand, candidate genes for high-temperature tolerance from anthers of three contrasting genotypes—Moroberekan (highly sensitive), IR64 (moderately tolerant), and N22 (highly tolerant)—have been identified using 2D gel electrophoresis (Jagadish et al 2010a). Some promising candidate genes, including several heat shock proteins, are now known. These genes are being analyzed in detail and a transgenic approach is used to assess whether these genes are involved in enhancing spikelet fertility under high-temperature stress.

Conclusions

The results of controlled-environment studies related to basic physiological processes such as photosynthesis and respiration have to be interpreted with caution and field studies on temperature effects should likewise consider other climatic variables before any meaningful conclusion is drawn. In the future, water-saving technologies such as alternate wetting and drying, aerobic rice, and direct seeding could be affected by high-temperature stress. Through existing research networks at IRRI—the Consortium for Unfavorable Rice Environments and the International Rice Heat Tolerance Nursery—systematic monitoring of temperature effects in vulnerable regions and different rice production systems will help in devising strategies to mitigate the negative impact. The two different approaches at IRRI have the ultimate goals of identifying stable QTLs/genes and providing breeders with donors and molecular markers that facilitate the introgression of these traits into locally adapted rice cultivars. This will help ensure sustainable rice yields under a warmer climate in the future.

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Facilitating mitigation projects in the land-use sector: lessons from the CDM and REDD

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Terrestrial ecosystems are vital to the global carbon cycle. It is estimated that about 60 gigatons of carbon (Gt C) are exchanged between terrestrial ecosystems and the atmosphere every year, with a net terrestrial uptake of about –0.9 ± 0.6 Gt C per year from 2000 to 2005 (Denman et al 2007). The world's tropical forests are estimated to contain 428 Gt C in vegetation and soils. The loss of tropical forests is the major driver of the CO_2 flux caused by land-use changes during the past 2 decades. The best estimate of the IPCC is that land use, land-use change, and forestry (LULUCF) activities, mainly tropical deforestation, contributed 1.6 Gt C per year of anthropogenic emissions in the 1990s (Denman et al 2007).

The tropical region has the largest potential for climate change mitigation through its good forestry activities (Nabuurs et al 2007). Reducing deforestation is a high-priority mitigation option within the tropical regions. In addition to the significant carbon gains, substantive environmental and other benefits could be obtained from this option. To counteract the loss of tropical forests, successful implementation of mitigation activities requires an understanding of the underlying and direct causes of deforestation, which are multiple and locally based (Chomitz et al 2006).

In the short term (2008-12), it is estimated that 93% of the total mitigation potential in the tropics will be avoided by deforestation (Jung 2005). In the long term, it is estimated that US$27.20/t CO_2 is needed to virtually eliminate deforestation (Sohngen and Sedjo 2006). Over 50 years, this could mean a net cumulative gain of 278,000 million t CO_2 relative to the baseline and 422 million ha of additional forests. The largest gains in carbon would occur in Southeast Asia, which gains nearly 109,000 million t CO_2 for $27.20/t CO_2, followed by South America, Africa, and Central America, which would gain 80,000, 70,000, and 22,000 million t CO_2 for $27.20/t CO_2, respectively.

There are still very few takers of forestry carbon projects under the so-called Kyoto market. As of this time, there are 14 registered A/R projects under the Clean Development Mechanism (CDM) of the Kyoto Protocol comprising only about 1% of all CDM projects. It has been estimated that up to 13.6 million carbon credits may be available by 2012 based on projects in the pipeline (Neef et al 2007). The situation in the voluntary carbon market (non-Kyoto) is slightly more encouraging. The voluntary over the countervoluntary markets are currently the only source of carbon financing for avoided deforestation and they have a higher proportion of forestry-based credits out of total market transactions than the CDM (36% vs 1% for CDM) (Hamilton et al 2007). Indeed, forest projects are the largest component of the voluntary carbon market, which, in 2006, amounted to 23.7 million t CO_2 valued at $91 million. This is partly due to the fact that voluntary carbon markets have historically served as sources of experimentation and innovation.

There is rising interest in the Philippines in participating in the emerging carbon market such as the CDM (Villamor and Lasco 2009). Several reforestation and agroforestry projects are under development in the last few years, although none has been registered with the CDM Executive Board. The purpose of this paper is to draw lessons, which can be applied to the development of agricultural carbon projects. Because the evolution of the forestry carbon market is in a more advanced stage, these lessons could prove valuable in avoiding the costly and time-consuming process that forestry projects are undergoing.

Lessons learned from CDM and REDD

Key issues in reducing emissions from deforestation and forest degradation (REDD) at the national and subnational levels that need to be addressed include transaction costs, measuring and monitoring of carbon benefits, equitable payment schemes, protecting small farmers' and indigenous people's rights, governance, promoting co-benefits, and multiple stakeholders.

High transaction costs

Drawing lessons from the CDM, high transaction costs could derail REDD implementation. The transaction costs of forestry CDM projects can be as high as $200,000 (Neef and Henders 2007). This could prove to be the most significant barrier to project fruition.

In addition, carbon credits may not be enough to cover the cost of actual project development. For example, in the Philippines, the income from carbon credits is not sufficient to recover the cost of tree planting (Lasco et al 2010, Lasco 2008). Using standard Department of Environment and Natural Resources (DENR) costs, planting and maintenance costs amount to about $1,000 in the first 3 years. In contrast, income from carbon credits is estimated to be about $250 ha^{-1} for 10 years (at 5 t C ha^{-1} per year and $5 per t C). This implies that carbon credits are best used as a supplemental source of income for farmers and project developers.

In developing carbon projects for agriculture, efforts must be made to reduce transaction costs to the minimum without sacrificing the technical soundness of the projects.

Measuring and monitoring carbon benefits

Measuring and monitoring carbon benefits pose huge challenges, especially for forest degradation. Monitoring refers to the collection of data and information at a national level and doing the necessary calculations for estimating emission reductions or enhancement of carbon stocks (and their associated uncertainties) against a reference level (Angelsen et al 2009, The Terrestrial Carbon Group Project 2009). More simply, it is the process of national monitoring of greenhouse gas-based performance of REDD interventions.

Of particular challenge to countries like the Philippines with little deforestation is the measurement of forest degradation or loss of forest biomass. Unlike deforestation, monitoring changes in carbon stocks of forest remaining as forests—including degradation, sustainable forest management, conservation, and enhancement of carbon stocks—can be more challenging, and, for some activities, the climate benefit is relatively smaller than the technical challenges. The IPCC guidelines are fairly good for deforestation but less developed for degradation.

Developing countries like the Philippines have practically no experience in measuring and monitoring forest carbon degradation and this is a significant gap. Investments must be made in building this capacity if the country is to engage in REDD+ activities.

Under the CDM, measurement and monitoring protocols have to be approved by the United Nations Framework Convention on Climate Change. This adds another layer of cost, although CDM developers can adopt pre-approved methods to reduce cost. In addition, monitoring is done by a third party, usually coming from a developed country. This is another major expense as each monitoring can cost $20,000.

Agricultural projects must develop tools and methods that are effective yet cost-efficient. Research institutions such as IRRI can help do this to enable small farmers to gain access to the carbon market.

Equitable sharing of carbon benefits

Payment schemes must be shared fairly, especially among local farmers and land managers. So far, there is very limited experience on how this can be done as a result of the limited number of CDM and REDD projects in developing countries. In Indonesia, the government is exploring a minimum proportion of carbon income to go to small farmers.

Rights of local and indigenous people

The rights of local and indigenous peoples may also be threatened under REDD. Once new carbon-financing schemes are available, property rights issues may become important. Competition on who will control forest lands may intensify. In the Philippines, many upland areas are being claimed by indigenous people. Such claims may be ignored in favor of establishing climate-change forests. Thus, there should be adequate provisions for respecting the rights of local users. This is easier said than done in many developing countries. These issues could be adequately addressed, however, through public consultation and participation in project planning and implementation. As an example, one way to do this in the Philippines is through the environmental impact assessment (EIA) system, which is already institutionalized in the country (Lasco et al 2010). Existing policies and procedures embodied in the Indigenous People's Rights Act (IPRA) should also be considered to ensure that the rights of indigenous people are fully safeguarded.

Governance

The ability of national and local institutions to manage the REDD process needs to be addressed through a capacity-building program. For example, in the Philippines, the capacity of the DENR as well as of other local government units to implement and monitor REDD at the national and local levels is still weak. A capacity-building program must be undertaken to enhance the capacity of various agencies of government and its civil society partners. It is estimated that such a national program can cost up to $2–3 million.

Multiple goods and services from forests

Forests produce many other goods and services other than carbon, which must also be protected. In other words, the multifunctionality of the landscape must be recognized. For example, forests in watersheds are expected to help provide a stable water supply for domestic use, irrigation, and power production, among others. These other uses must be taken into account in the development of REDD projects. Similarly, agricultural landscapes have multiple functions as well, which must be considered in designing carbon projects.

Numerous stakeholders

Finally, because of the aforementioned factors, many stakeholders are concerned about how forests are managed. These include farmers, hydropower companies, irrigation associations, and eco-tourists. Their interests will have to be considered in forest carbon implementation.

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

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One of the main consequences of climate change is an increase in the frequency and severity of abiotic stresses. Higher temperatures will particularly have 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. Tolerance of all of these abiotic stresses is 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. This work has been in progress for the unfavorable rainfed areas, and new drought-, submergence-, and salt-tolerant 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 of 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. Despite efforts for more than 30 years to develop tolerant varieties, farmers are still growing susceptible varieties or low-yielding local landraces.

The prospect of global warming attributed to the accumulation of greenhouse gases is causing major concern, especially on 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 levels will result in the loss of some lands currently used for producing 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 the 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 drought, flooding, salinity, and high temperature will have some protection against the effects of climate change. Fortunately, recent progress in developing stress-tolerant varieties gives some optimism about the prospects for developing "climate-proof" rice varieties. Projects such as the Bill & Melinda Gates Foundation-funded STRASA (Stress-Tolerant Rice for Africa and South Asia) are making rapid progress in providing technology for farmers in unfavorable areas. This 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 quantitative trait locus (QTL) mapping have been conducted intensively over the last 20 years. These studies have focused on direct measurements 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 2008).

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 major effects 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. The 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

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[1] Based on a paper from the CURE Workshop on Climate Change, 4 May 2010, Siem Reap, Cambodia.

cross between tolerant variety Apo and 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 1 t ha^{-1} yield advantage under stress. Most of the popular varieties collapse under these conditions.

Submergence tolerance

Submergence can affect rice crops at any stage of growth. This can be short-term (i.e., flash floods) or long-term (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 suppression of the normal elongation response of rice varieties when under water. This suppression of elongation enhances survival by reducing carbohydrate consumption and 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 (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.

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
PSB Rc82-Sub1 (IR09F434)	115–118	102–105	20

Tolerance during germination and early seedling growth is important for direct seeding in both irrigated and rainfed conditions (Ismail et al 2009). Varietal differences in submergence tolerance during germination have also been observed. 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).

Long-term "stagnant" flooding is common in low-lying areas and is expected to be an increasing problem in delta areas that will be affected by rising sea levels. If the water level remains at around 50 cm or lower, 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 the 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 early and have a rapid rate of internode elongation early in their growth. The early initiation of elongation is controlled by QTLs on chromosomes 3 and 12 (Nemoto et al 2004, Hattori et al 2007). The rate of internode elongation is controlled by QTLs on chromosomes 1 and 12 (Hattori et al 2007, 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, *SNORKEL1* and *SNORKEL2*, which controlled this elongation response (Hattori et al 2009). The genes are very similar to *SUB1* but the latter seems to suppress elongation.

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 give 1–2 t ha^{-1} yield advantage over the susceptible varieties, but they can have more 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 saltwater 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 conferred salt tolerance on chromosome 1; it was designated *Saltol* (Bonilla et al 2002) and has been the target of marker-assisted selection (Thomson et al 2010). On chromosome 1, QTL *SKC1* was isolated by positional cloning and was determined to be a protein that functions as an Na^+-selected transporter (Ren et al 2005). Besides *Saltol*, several other major QTLs are being identified and targeted for marker-assisted backcrossing to combine them with *Saltol* for higher tolerance.

Considerable progress has been made in developing improved varieties with tolerance of salinity, particularly for 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 with the *Saltol* locus for salinity (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. Thus, 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 and 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 high-temperature tolerance during anthesis have been identified and initial genetic studies have been performed (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 high-temperature tolerance in rice.

Conclusions

Rapid progress has been made to incorporate tolerance of drought, submergence, and salinity stresses into improved varieties, and many of these are now being disseminated to farmers in unfavorable regions. These varieties have the potential to give at least 1 t ha^{-1} yield advantage under stressed conditions while performing similar to or better than farmers' present varieties under favorable conditions. To ensure that future rice varieties are adapted to predicted 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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National policy and programs for adaptation to climate change in Bangladesh

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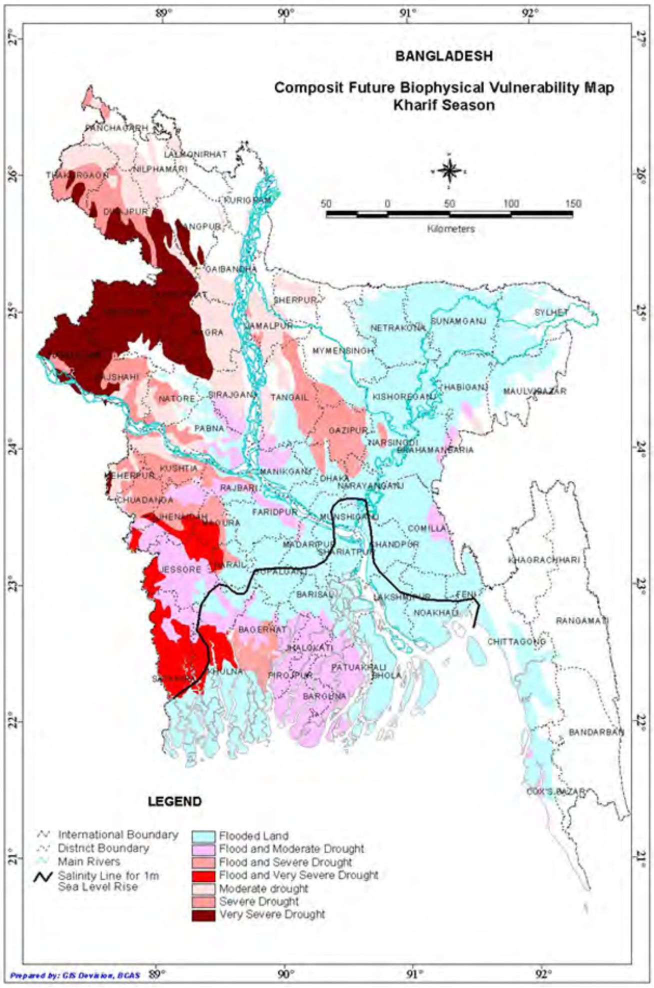
Bangladesh is one of the countries most vulnerable to climate change. The country is located in a geophysically critical area, with the great Himalayas in the north and the Bay of Bengal in the south. It has three big river systems, a large deltaic floodplain, and a long coast, all susceptible to frequent floods, cyclones, tidal surges, salinity intrusion, and sea-level rise. The temperature rise and erratic rainfall, induced by global warming, have already modified weather and seasonal patterns, which in turn affected agricultural productivity and the livelihood of millions. The country has a large and growing population, the majority of whom are poor. They very often depend on agriculture and the natural resource base for employment, income, and livelihood. Climate variability and climatic extremes such as floods, cyclones, and tidal surges damage agricultural productivity, livelihood resources, fresh water and health, and employment and income of the common people. As agricultural productivity will be severely affected by climate change, this can threaten the food security of millions of the poor and marginalized people in Bangladesh.

The people in general and the government in particular have very limited capacity to address the increasing impacts of global climate change and the risks associated with it. Notwithstanding, the government of Bangladesh formulated the National Adaptation Programme of Action (NAPA) in 2009 and the Bangladesh Climate Change Strategy and Action Plan (BCCSAP) in 2010 to address climate change issues and their impacts on society, the economy, and ecosystems (MOEF 2009, 2010). Research organizations, civil society organizations, and nongovernment organizations (NGOs) are also involved in raising awareness about risks and vulnerability to climate change in Bangladesh. For instance, the Bangladesh Centre for Advanced Studies (BCAS) is trying to promote adaptation to climate change with a particular focus on livelihood, agricultural development, and disaster risk reduction. A few NGOs are also helping the government to raise awareness and implement the activities recommended by NAPA and BCCSAP.



Climate-affected zones in Bangladesh.

Country context: risks and vulnerability

The country is already affected by climate variability (temperature rise, drought, and changes in precipitation), other related factors (sea-level rise, salinity intrusion, and submergence), and climatic extremes such as floods, cyclones, tidal surges, heat stress, and cold waves. These affect land and soil conditions, water source and quality, biodiversity and natural resource base, and the livelihood of the common people (MOEF 2009). The coastal zone, the central floodplain, and the northwestern upland areas are the worst affected. Bangladesh has a long coast, and many areas along the coastal zone experience high salinity, inundation of low-lying areas caused by high tide and sea-level rise, cyclones and tidal surges, along with temperature rise and erratic rainfall. Almost two- thirds of the country is floodplain. The frequency and intensity of floods have increased because of glaciers melting in the Himalayas and heavy rainfall upstream. Devastating and prolonged floods come every 4–5 years, greatly affecting agriculture. Bangladesh has some upland areas in the northwest and a few hilly areas in the northeast and southeast. The northwestern region is affected by low rainfall and drought, whereas the hilly areas experience heavy rainfall in some years, causing flash floods and landslides. The map shows the climate-affected zones in Bangladesh. Crop production and agricultural activities are badly affected in all major ecosystems.

Impacts on agriculture

Agriculture is the mainstay for a majority of the people in Bangladesh. More than 65% of the population depends on agriculture for employment, income, and livelihood. It contributes about 25% of gross domestic product and provides food and nutrition to more than 150 million people. Bangladesh is predominantly a rice-growing country. Cash crops, vegetables, and fruits are also grown on a limited scale. Crop production is largely determined by temperature, rainfall, humidity, and flooding. The country is already facing many agroecological problems, including a decrease in soil fertility, land and water pollution, loss of biodiversity, high input costs, and low economic returns. Climate change constitutes an additional threat to agricultural development and the food security of the people. Global warming and rapid changes in seasonal patterns and weather conditions, uneven rainfall and hydrological patterns (i.e., too much water during the monsoon season and too little water during the dry season), drought, salinity intrusion, and other extreme events are affecting soil conditions, land fertility, and agricultural productivity. Water management and irrigation are also influenced by climate change and climatic extremes, which have negative consequences on agriculture and food security.

Agriculture in Bangladesh is influenced by seasonal characteristics and such climate variables as temperature, rainfall, humidity, daylength, etc. (MOEF 2009). It is also often constrained by the occurrence of disasters such as floods, droughts, soil and water salinity, cyclones, and storm surges. Studies indicate that climate is changing and becoming more unpredictable every year in Bangladesh. There is a strong possibility that the moisture content of the topsoil in the northwestern region of the country will decrease substantially, the result of the decrease in water precipitation and higher evapotranspiration.

Degradation of productive land, including quality and physical losses, is a key concern for coastal agriculture due to salinity intrusion and sea-level rise. Drainage congestion and waterlogging are very likely in the coastal region because of the combined effects of higher sea water-level subsidence, sedimentation of estuary branches, higher river beds, and reduced sedimentation in flood-protected areas. The higher temperatures and the changing rainfall patterns, coupled with increased flooding, rising salinity in the coastal belt, droughts in the northwest and southwest, and drainage problems, will likely reduce crop yield and crop production. The results of a Decision Support System for Agro-Technology Transfer (DSSAT) model show that yield reduction will vary by types of crop and growing season. It is estimated that, by 2050, rice production in Bangladesh could decline by 8%; that of wheat is predicted to be about 32%. A few studies indicate that a rise of 1–2 °C, in combination with lower solar radiation, causes sterility in rice spikelets. High temperatures were found to reduce the yields of high-yielding aus, aman, and boro rice in all study locations and in all seasons. The effect was particularly evident with a temperature rise of 4 °C. Climate changes, especially in temperature, humidity, and radiation, greatly affect the incidence of insect pests, diseases, and microorganisms. A 1 °C change would increase the virulence of some races of rust that infect wheat. The production of crops in Bangladesh is constrained by too much water in the wet season and too little water in the dry season.

Since climate change poses a serious threat to agriculture, food security, and nutritional status of the common people in Bangladesh, the country as a whole and the affected communities require greater adaptive capacity to address the impacts of climate change. Farmers and members of the community implement measures to cope with the changes. But these local coping mechanisms and autonomous adaptation are not adequate in the context of rapid climate change and extreme events such as prolonged floods, worsening drought conditions, salinity intrusion, and frequent cyclones. They need new information about the increasing risks, and they must be aware of new technologies, skills, and resources to help them improve their adaptive capacity.

National policy and strategies for adaptation

The government of Bangladesh, the research institutes, civil society organizations, and many NGOs in Bangladesh are quite aware of the growing risks and the vulnerability of the country to climate change. The government has already prepared the NAPA as an immediate response to climate change. Very recently, the government also formulated the BCCSAP to promote climate-resilient development in the country. The Bangladesh Ministry of Environment and Forest is the national focal point for both NAPA and BCCSAP, with the National Steering Committee on Climate Change providing guidance. The relevant ministries and government departments provided inputs to NAPA and BCCSAP. National experts and civil society groups were also consulted to make these strategies and action plans more comprehensive and acceptable to all major stakeholders. The Bangladesh NAPA followed the UN guidelines, while BCCSAP upheld the four building blocks of the UNFCCC Bali Action: adaptation, mitigation, technology generation, and capacity building.

The main aim of BCCSAP is to promote climate-resilient development and a low carbon economy in Bangladesh. The strategy document has two parts. The first part provides background information about the physical context and major climate impacts, the socioeconomic reality, and the rationale behind the strategy. The second part elaborates on a set of programs based on six key pillars covering the broad thematic areas of adaptation and mitigation interventions. These include food security and social protection, comprehensive disaster management, protection of resources and infrastructure, mitigation and a low carbon economy, research and knowledge management, and capacity building and institutional integration.

The first broad area of intervention focuses on “food security and social protection,” which again emphasizes adaptation in agriculture. The main programs identified under this thematic area are development of climate-resilient cropping systems in all agroecological systems; adaptation against drought, salinity, and flood; and institutional capacity building for research toward climate-resilient cultivars (MOEF 2010). The government has already allocated some resources from the annual budget to implement the identified projects. The Bangladesh Agricultural Research Institute, the Bangladesh Rice Research Institute, and the Bangladesh Agricultural Research Council are also involved in the implementation of the adaptation projects.

NGO and civil society engagement

Bangladesh has a thriving NGO community that is engaged in rural development, mass education and awareness, women’s empowerment and gender role promotion, natural resource management, and environmental conservation. Also concerned about climate change impacts, they are helping the government and vulnerable communities to promote adaptation for reducing their risks and vulnerability. The BCAS, as an independent research and policy institute in Dhaka, has long had a key focus on climate change issues. It is working with vulnerable communities and local actors to understand risks and vulnerability relating to climate change in selected climate-affected areas in the floodplain, upland, and coastal zones. BCAS is building local capacity to develop adaptation strategies and action plans; the adaptation activities focus on agriculture, water, health, livelihood, and disaster risk reduction (see box for an example of local adaptation). BCAS, in association with partners, has organized international conferences in Bangladesh on community-based adaptation (CAB) approaches and practices. BCAS is likewise assisting the government in implementing NAPA and BCCSAP.

A few national NGOs (e.g., BRAC, RDRS, GUK) and some international development organizations (e.g., Care International, Action Aid, Oxfam GB, and FAO) are trying to integrate climate change adaptation into their development programs. FAO and ADPC have completed an interesting study on adaptation in drought-prone areas in Bangladesh. The study conducted climate risk assessment at the community level to improve the community’s understanding of climate variability and its impacts on agriculture and livelihoods in northwestern Bangladesh. It is expected that the recommended adaptation options and strategies will facilitate agricultural and sectoral development in the region.

The challenges ahead

The country faces many big challenges. We have to increase productivity and promote sustainability in agriculture to ensure food security, alleviate poverty, and reduce disaster risks. At the same time, we have to promote adaptation to climate change. All these are interlinked and our challenge is to address these simultaneously. In relation to promoting adaptation in agriculture (which is the biggest challenge for Bangladesh), we have to innovate and promote new and climate-resilient crop varieties with higher productivity but that require less external inputs. Short-maturing rice varieties and those with tolerance for flood/submergence, salinity, and drought should be introduced in the climate-affected zones immediately, along with other crops as well. R&D efforts in agriculture should be further strengthened as climate and weather conditions are changing very fast. Capacity building within farming communities, agricultural extension departments, research institutes, and development agencies is urgently needed to ensure adaptation at the local and regional levels.

Local capacity building for advancing community adaptation to climate change

The Bangladesh Centre for Advanced Studies (BCAS) has undertaken an action research project for advancing community adaptation to climate change through building local capacity and resilience in selected areas in the floodplain and coastal zone (BCAS 2008). The project aims to enhance community resilience and adaptive capacity of the poor and local actors to reduce risks and vulnerability relating to climate variability and climatic disasters. The action research project undertakes a participatory and multidisciplinary approach to understand the risks and to identify local adaptation options. Capacity building is a key focus of the project. The project defines local capacity in terms of enhanced awareness, generation of new knowledge and information sharing, engagement of community people, skill development of local actors for integrating adaptation into local development (agriculture, water, health, infrastructure, and rural development etc.), livelihood promotion, and disaster risk reduction (DRR). The project puts a lot of effort into building the capacity of the poor, marginalized groups, women, and local development actors through various schemes—awareness raising, social mobilization and group formation, orientation and training on climate change risk, vulnerability and adaptation, information and knowledge sharing, skill development, and enhancement of linkages between the community and local government bodies/sectoral agencies (e.g., the department of agricultural extension services, water boards, departments of rural development, public health, and disaster preparedness). The project further promotes good practices in agricultural diversification, freshwater conservation and health promotion, protection of the resource base and livelihood, and improving DRR practices at the family and community levels. It is expected that collective local action build resilience in the human, social, and natural systems and thereby ensure better adaptation to current and future climatic conditions.

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Farmer field schools for climate adaptation to enhance farmers' resilience to climate change

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The reality of climate change and its impact on global crop production calls for a paradigm shift in methods of adaptation, especially by poor rural farmers in developing countries. In rice culture, the production of greenhouse gases from paddy fields and minimizing their effects on the global environment together with the emerging knowledge of water shortage for crop production and in agropastoral systems demand policy directions that will take full cognizance of this changing trend. New technologies that are generated often get to farming communities through national agricultural research and extension systems and also through the farmer field school (FFS) system. But, with the need to quickly adjust and adapt to climate change, this paper proposes a broad-based FFS approach in which new curricula will incorporate monitoring the changes in the production environment. This will have to be based on developing new skills for the training of trainers component of this extension method and on farmers' own socio-cultural circumstances. This is necessary to develop the requisite resilience of farming communities to climate change. FAO believes that, once farmers understand the biological processes of their production environments and adjust their cultivation and cultural practices, the desired long-term resilience to climate change can be achieved.

Since the advent of farmer field schools (FFS) in the 1980s for rice-based cropping systems (and, with their evolution, for other crops as well, there is a huge potential to use this farmer training and learning methodology in farming communities affected by climate change (CC). As an adult learning methodology, FFS have been used to train millions of farmers worldwide, and their influence is still growing. A global survey in 2005 estimated that, by 2008, 10–20 million farmers would have graduated from FFS. These are still active in Asia (East, Southeast, South, Central, and Middle East), Africa (Western, Southern, Eastern, and Central), Latin America, South and Central America, the Caribbean, Eastern Europe, and, recently, Western Europe (Denmark) and the U.S. (Braun and Duveskog 2008). In view of the usefulness of this learning methodology and its global appeal, there is a renewed interest for it to be used by communities affected by CC. The basic concepts that allow adult farmers to learn and share knowledge using a bottom-up approach may need a clear reorientation and curricular development and adjustment so that it can be used by communities in managing their fragile farming ecologies. This is the focus of this paper.

It is common for technocrats, governments, and researchers to think through and propose new technologies to combat CC. How to effectively convey ideas about CC is probably more difficult than developing the technology itself because of the sociological and economic circumstances of the clientele. This is probably where the use of modified curricula for FFS is important, especially when communities are heterogeneous and sociologically different. In the specific case of rice and rice-based cropping systems, the challenges and opportunities are not different. The issues of new varieties and good seed to respond to increasing temperatures in tropical countries and humid zones as well as the occurrence of drought, new tidal heights in flood-prone areas and deltas; the emergence of new diseases in areas where they were previously unknown, new pests and migratory birds, salinity, nutrient deficiency or toxicity, and CH_4 and CO_2 emissions in paddy fields are a few of the many constraints that must be managed by rice farmers in the face of CC.

As noted by Settle and Garba (2009), farming systems worldwide have been going through dramatic changes as a result of globalization, liberalization, and rapid urbanization. Moreover, the public extension service has been in decline. Indeed, in recent times, the effects of CC have made adjustments by farmers even more critical. The general belief is that, without a functional extension-research infrastructure in place that will interact and influence farming methods, the hoped-for improvements in agronomic practices by millions of smallholder farmers are unlikely to materialize. The question therefore is how to engage these same farmers who are confronted with changes in their farming setup to cope with them.

The Food and Agriculture Organization (FAO) of the United Nations (UN) is proposing an adaptation of the FFS methodology enable farmers to manage the changes in their cropping and farming environments. For example, Settle and Garba (2009) noted that farmers need to know how soil amendments promote the action of soil-based organisms, which facilitate access to key nutrients and suppress plant diseases; how insects and worms help build a healthy soil structure, which in turn promotes water- and nutrient-holding capacities and recharges groundwater resources; or how native pollinators and predator insects can be conserved to enhance key ecosystem services that contribute to more efficient farming systems. Thus, without some practical form of education, farmers rarely have access to this kind of knowledge. Without a clear understanding of these processes, it will be difficult for farmers to appreciate the changes that may occur in the farming environment and to make the necessary adjustments for them. FAO is calling for initiatives aimed at producing crops sustainably and this demand will involve a complex mix of domesticated plant and animal species and associated management techniques requiring farmer skills and knowledge (Settle and Garba 2009). To increase production efficiently and sustainably, farmers need to understand the conditions in which agricultural inputs (seeds, fertilizers, and pesticides) can either complement or hamper biological processes and ecosystem services that inherently support agriculture so they can adjust if circumstances change.

In this paper, we review briefly the importance of rice in the global economy and present some thoughts on the abundance and lack of water, its pollution, and some of the basic concepts of sustainable crop production and intensification. This paper, however, will draw conclusions on how much is needed to make FFS respond to CC under farmers' circumstances, presenting elements on how to monitor changes within the farmer setup as the agroecology is affected by changes in climate.

Rice in the global setup

Rice is the world's single most important food crop and a primary food source for about half of the world's population. Rice was considered a staple food for 3.31 billion people in 2002. It is planted on about 148 million ha annually or on 11% of the world's cultivated land (Khush 1997). In terms of food energy derived from rice, 3.08 billion people showed very high dependence on rice for food calories (>800 kcal person^{-1} day^{-1}). Globally, Nguyen (2002) reported that the cultivation of rice extends from drylands to wetlands and from the banks of the Amur River at 53° North latitude to central Argentina at 40° South latitude. The wide expanse of land available for rice cultivation suggests that the commodity will be most affected by CC. For example, rice is grown in cool climates at altitudes of over 2,600 m in the mountains of Nepal and in the hot deserts of Egypt. Most of the annual rice production comes from tropical climate areas. In 2004, more than 75% of the global rice harvested area (about 114 million out of 153 million ha) came from the tropical region, whose boundaries are formed by the Tropic of Cancer in the Northern Hemisphere and the Tropic of Capricorn in the Southern Hemisphere. The tropical region includes all Southeast Asian countries, Bangladesh, Sri Lanka, almost all the rice-growing states of India, almost all rice-growing countries in sub-Saharan Africa, and the majority of rice-growing areas in Latin America and the Caribbean.

Methane (CH_4) emissions from flooded rice soils have been identified as a contributor to global warming. Water regime, organic matter management, temperature and soil properties, and rice plants, are the major factors determining the production and flux of CH_4 in rice fields. Results of studies during the 1990s, however, showed that CH_4 emissions from rice fields were actually much lower than originally thought, accounting for only about 10% of total global emissions (Maclean et al 2002). Varietal differences could be used to lessen CH_4 emissions in rice production. Also, intermittent irrigation or alternate wetting and drying (AWD) could reduce emissions from rice fields, while the transfer and adoption of a rice integrated crop management approach (e.g., the Australian RiceCheck) would increase the efficiency of nitrogen fertilizer use in rice production, thus reducing nitrous oxide emissions (Nguyen 2002). In addition, initial results obtained from rice-wheat systems in China and India demonstrate that the fossil fuels used in land preparation operations in rice-based systems could be substantially minimized using conservation agriculture practices such as minimum and reduced tillage (T. Friedrich, personal communication, cited by Nguyen 2002).

FAO and sustainable cropping intensification

Globally, to respond to the adverse effects of CC, FAO proposes to use the ecosystem approach to make the production base more resilient and responsive to future needs. Indeed, FAO points out that land per capita will decrease from 4.3 ha as it was in 1961 to 1.5 ha in 2050. Also, there will be erosion in ecosystem services while the annual growth rate of major cereals will decrease from 3.5% in 1980 to 1% in 2050. FAO proposes a system of sustainable crop production intensification (SCPI) as the main strategic objective to stabilize world food production. Many other organizations and academics have also alerted the world on the need for a sustainable production of crops with a focus on conserving soil and other natural resources.

It is understood that rainfed crops such as upland rice are likely to be worst hit by CC because of the limited mechanisms for coping with variability of precipitation. Many workers have proposed that developing mechanisms for adaptation in rainfed rice production can be seen as a promising entry point to buffer the consequences of CC among the poorest of the poor. It is known that CC will aggravate a variety of stresses for rice plants—for example, heat, drought, salinity, and submergence. Improved tolerance of these abiotic stresses has always been at the heart of research institutions dealing with agricultural production in unfavorable environments (Wassmann et al 2009). Climate change will also affect rice production through rising sea levels. IPCC (as cited by Nguyen 2002) reported that model projections of future global mean sea-level change, based on temperature change projections, show a rise of between 13 and 94 cm by 2100, with a central estimate of 49 cm.

Though many opportunities and concepts are waiting to be harnessed for rice-based cropping systems in the face of global CC, only a few of them are elaborated upon:

- Inclusion of legumes in cropping systems and maximizing benefits from biological nitrogen fixation (BNF)
- Use of conservation agriculture (CA) as a basis for preserving the soil and its biological components
- Increased use of rotations and, where possible, improved use of fallow through grasslands
- Increased use of agroforestry systems

- Efficient management of water resources
- Use of integrated production and pest management (IPPM) and FFS strategies

Inclusion of legumes in cropping systems and maximizing the benefits from BNF

The soils that upport the livelihood of many in the developing world are poor in nutrients and are of poor clay types. There is a need to cushion them from the depletion of the basic nutrients that they supply to crops. BNF, especially that associated with legumes, has great potential to contribute to productive and sustainable agricultural systems for the tropics, but more research is required to investigate how biologically fixed N and the increased BNF contributions resulting from research innovations can be incorporated into viable agricultural systems to increase crop or pasture yields and to substitute for N fertilizer inputs. Any green manure crop used primarily as a soil amendment and a nutrient source for subsequent crops may provide such an alternative. Unlike synthetic N fertilizers, legumes used as green manure represent a potentially renewable source of on-farm, biologically fixed N and may also fix and add large amounts of C to cropping systems. Hence, they are central to the notion of sustainability.

Use of CA as a basis for preserving the soil and its biological components

Conservation agriculture is an important crop cultivation method proposed by FAO to deal with sustainable crop production in the face of CC. CA aims to conserve soil resources while achieving sustained high production profitably. FAO (2009) believes that, by using CA, the following are achieved:

1. Aerobic processes in porous soils with continuous macropores that facilitate aeration and gaseous exchange between soils and the atmosphere and allow deep drainage of excess water to recharge groundwater.
2. Organic matter that provides nutrient and energy substrate for soil microorganisms.
3. A stable environment without abrupt changes in temperature, humidity, salt concentration, or pH.

FAO believes that continuous and simultaneous application of CA can increase soil life and biodiversity, enhance biological processes related to soil productive capacity and crop nutrition, and provide an environment conducive to the growth of soil microorganisms.

Use of grassland and agroforestry in fallow and rice-based systems

Grassland management provides important ecosystem services. Grasslands offer a strategic opportunity to enhance ecosystem processes, including carbon sequestration, water capture and retention, and biological diversity while sustaining food-producing landscapes, livelihoods, and lifestyles. Grasslands host more than 10,000 plant species, including important medicinal plants, and are vital to maintaining wild and cultivated genetic resources *in situ*. They provide ground cover to protect many fragile environments. Good grazing land management is considered to have the second most important technical mitigation potential as these systems have potential to sequester 0.2–0.8 Gt CO_2 per year until 2030, depending on the practices imposed.

When trees are added to these systems, sequestration rates increase dramatically. Grassland cover can capture 50–80% more water than bare ground, thus reducing the risk of droughts and floods and increasing groundwater recharge. These attributes taken together are critical for CC mitigation and adaptation.

Grasslands and forages are important components of crop-livestock systems. Improved crop intensification and diversification practices, through the introduction of forage legumes and mixed grass-forage species, efficient soil, manure, and plant nutrient management, and diversification of crop and livestock production at the farm level, contribute to increased productivity and stability of incomes, efficient use of soil and water resources, and improvement of the CC mitigation and adaptation potential of rice-based systems. When trees are brought into crop-livestock (agro-silvopastoral) systems, these benefits are further enhanced.

Water scarcity and pollution

Water use has been growing globally at more than twice the rate of population increase in the last century, and an increasing number of regions are reaching the limit at which reliable water services can be delivered. Rapidly growing urban areas and industries increase pressure on the quality and quantity of local water resources. The agricultural sector (including livestock) accounts for about 70% of all withdrawals of water worldwide, and up to 95% in some developing countries. Irrigated agriculture provides about 40% of the global food supply on 20% of cultivated land. FAO estimates that, in developing countries in the next 30 years, effective irrigated area will increase by 34% and 14% more water will be withdrawn for agricultural purposes.

Agricultural runoff containing nutrients such as fertilizers and agrochemicals/pesticides is the main source of nonpoint-source water pollutants. In the European Union (EU), inorganic nitrogen use in agriculture rose from around 1 million t annually in 1950 to a peak of 11 million t in mid-1980. More recently, it fell to approximately 10 million t. The nitrogen “pressure” on agricultural soils from animal husbandry is also estimated at 8 million t annually. In high-income countries, total commercial fertilizer consumption in agriculture has slowed down since 1990, but emerging economies and developing countries still have high fertilizer use.

Use of integrated production and pest management (IPPM) and FFS strategies

The genesis of integrated pest management (IPM) was a response to the emergence of problems associated with the reliance on chemical controls for insect pests by governments, extension systems, and farmers in Asia. How the search for solutions to these problems led to the development of a more holistic view of what constituted an agroecosystem and how human intervention could either enhance or disrupt one has been recorded by Litsinger et al (1982). Today, FFS alumni are able to not only apply IPM principles in their fields but also master a process enabling them to help others learn and apply IPM-FFS principles and organize collaborative activities in their communities to institutionalize these.

Central to the popularity of FFS programs is an appropriate topic and methodological training of the people who organize and facilitate FFS. To be a successful FFS trainer/facilitator, one must have skills in managing participatory, discovery-based learning and technical knowledge to guide the groups' learning and action process. Without an adequate training of trainers (ToT) program, the subsequent FFS program will fall far of its potential (Luther et al 2005). Season-long in-house (residential) and field-based ToT courses in which all activities should follow an experiential learning approach have proven to be an effective model for building the required technical capacity of trainers.

As the FFS will always begin with an agroecosystem analysis, it should be possible for a curriculum to be fairly adjusted to suit CC adaptation. In an agroecosystem analysis in the classical FFS, crop growth stages, presence and abundance of pests and beneficial insects, weather, soil, and overall crop conditions in contrasting plots in an FFS are recorded by farmers each week on a poster using sketches and symbols. As an adaptation from Gallagher (2003) (cited by Braun and Duveskog 2008), these elements present the main elements of the approach when FFS was developed in 1989 and they are still in use during current FFS implementation.

Weather pattern

- Onset of the rainy season
- First/onset of sowing time
- Cropping calendar and changes
- Duration of cropping season
- Rainfall days
- Sunshine days/cloudy days
- Windy days/stormy days

General agronomic and crop protection

- Diseases and pests (including new weeds, etc.)
- Lodging and frequency of lodging
- Pests and natural enemies observed in fields
- Pests on one side, natural enemies on the other
- The plant (or animal), indicating the size
- Stage of growth, along with other important growth features such as number of stems/tillers, color of the plant and any visible damage, good fraction of fertilizer and best moment to input it
- Managing and preparing organic matter (doing compost)
- Important features of the environment (water level in the field)
- Sunlight, shade trees, weeds, and inputs

Postharvest

- Time of harvesting (delay or earliness and variety)
- Changes in ripening and harvesting time
- Presence or absence of water after harvesting
- Soil condition at harvesting (cracked or otherwise)

To achieve more precise adaptation mechanisms, FAO is proposing a methodology for monitoring CC indices so that mitigation approaches can be developed. Settle and Garba (2009) have proposed 13-point possible actions as elements that must be used to build resilience. These include building an effective communication strategy, developing action research links with national and regional research, establishing networks, etc. All will, however, depend on the region and the circumstances of the farmers**.**

Conclusions

Global rice-cropping systems are important for many poor people in the developing world and are most likely to be hard hit by climate change. Manipulating biological soil processes through carefully thought out actions should provide long-term solutions and resilience to upland rice-cropping systems. The role of IPPM and FFS will be crucial in managing fragile ecosystems and providing communities with the basic understanding of the modalities to cope with CC. FAO believes that developing strategies that will improve the biological functioning of fragile soils across this production system needs global support, and it must provide long-term aid to the communities living on this resource, as the effect of CC still looms large. A new paradigm in conducting and organizing a CC-based approach for FFS is being proposed. The circumstances of the community and farmers in question must be taken into consideration.

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An integration framework for social research and farming systems modeling to co-develop farmer-verified adaptation strategies in the context of climate change

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Understanding adaptive capacity as the basis for developing technical adaptation options to climate change

Vulnerability studies of varying depth and geographic extent have been conducted in many Asian countries, mostly in association with the National Adaptation Plan for Action (NAPA). Vulnerability assessments are undoubtedly useful in identifying hotspots where climate change impacts can be expected to be more adverse than elsewhere, particularly if they are spatially explicit (e.g., Yusuf and Francisco 2009). In consequence, these allow a more targeted approach to allocating limited resources toward climate adaptation.

However, a serious weakness of vulnerability assessments is that they generally focus only on potential threats (e.g., exposures, hazards, stresses, etc.) that may affect livelihoods and well-being rather than consider what people can do and are already doing to safeguard or improve their livelihoods. The focus on potential negative impacts of exposure and sensitivity to rising temperatures and other extreme events (e.g., cyclones, floods) tends to be disempowering for individuals, households, and communities that are unable to directly influence these drivers of change. Focusing on impacts is also disempowering because it overlooks the intrinsic adaptive capacity and demonstrated ability of affected populations to adjust positively to significant change.

Assessments of adaptive capacity are well positioned to consider the constraining and enabling factors for individuals, households, or communities to cope with various types of change. These typically link possible responses back to actions and behavioral change that households or communities are able to initiate using the resources at their disposal and taking environmental constraints into account (Gallopin 2006). Moreover, such assessments more readily lend themselves to uncovering actions that farming households are already undertaking, as managing climatic risk is nothing intrinsically new to people who are constantly adapting to socioeconomic, political, or market-related drivers of change (Bernstein et al 1992).

Roth et al (2009) recently concluded that research on adaptive capacity is lacking in Asia, although understanding how it relates to drivers of change is a prerequisite for selecting the most appropriate adaptation strategies. Moreover, the analysis of adaptive capacity ensures that adaptation strategies are not merely technically feasible but are also accepted by farmers as more profitable, less risky, and easier to adopt.

Brown et al (2010) and Nelson et al (2010) have recently applied the Sustainable Rural Livelihoods (SRL) framework (Scoones 1999, Ellis 2000) in Australia as a tool to assess adaptive capacity. Based on their results, a pilot study was conducted by Roth et al (2009) in two villages in the rainfed districts of Andhra Pradesh, India, and in two villages in Bhola District of southern Bangladesh. The SRL was primarily chosen because it has a substantial history in development practice, particularly in South Asia, and, as shown by Brown et al (2010), it is suitable to be used as a tool for assessing adaptive capacity in ways that are empowering at the local level. It also offers the prospect of enabling a higher level and more relevant policy assessments of adaptive capacity to be carried out (Nelson et al 2010).

Details of the methodology as tested in India and Bangladesh are provided by Roth et al (2009). In general, the principal conclusion of the pilot study is that, with some further refinement (e.g., basing the design of sampling and survey schemes on typologies of key farming situations), the SRL framework appears to be a useful tool at the local scale for farm households to self-assess their adaptive capacity in relation to climate change and other drivers of change. It also generated some useful insights with respect to the perceived priorities of farm households for adaptation measures. In the case study villages of Andhra Pradesh (Table 1), the sampled households from both villages considered that the highest priorities for action to strengthen their adaptive capacity were not necessarily associated with the traditional interventions to build natural capital (e.g., improved soil fertility) or infrastructure capital (e.g., groundwater bores, irrigation canals) but tended to be in the domain of increasing social and human capital. For example, typical interventions were about training, improving access to information, enhancing cooperative structures, and forming self-help groups.

Similar observations were made in the Bangladesh case study (Table 2), in which traditional interventions related to agricultural research (e.g., improving crop, water, and livestock management practices) were only a few of a long list of other possible adaptation interventions. Understandably, interventions that directly affect survival during catastrophes such as the construction of cyclone shelters will generally be more highly rated than incremental adaptation based on improving crop productivity in the face of gradual shifts in rainfall patterns. The critical point, however, is that, when undertaking research on crop and water management options that will assist farmers

Table 1. Farmer-assessed priorities for action to enhance adaptive capacity, mapped against the five capitals as defined in the Sustainable Rural Livelihoods framework, for two villages in Andhra Pradesh. Based on farmers' assessment of endowment with assets against each of the five capitals, the ranking of capitals was transformed into ability to adapt (e.g., high endowment with assets = good ability to adapt). This, in turn, corresponds to priorities for action (e.g., very good ability to adapt = low priority for further action to strengthen adaptive capacity). For details, see Roth et al (2009).

Village	Ranking of endowment with capitals			
	Low ← – – – – – – – – – – – – – – – – – – – → High			
Bairanpalli		Financial, human, and social	Natural	Physical
Srirangapur	Social	Financial	Human, physical, and natural	
	Ability to adapt			
	Total inability	Reasonable ability	Good ability	Very good ability
	Priority for action			
	High priority	Some priority for action and monitoring		Low priority

Table 2. Collective actions identified through farmer self-assessment workshops using the Sustainable Rural Livelihoods framework to enhance adaptive capacity in two villages in Bhola District, southern Bangladesh. Taken from Roth et al (2009).

Capital	Collective actions targeted at…
Human	Improving regional education and health services; community events; increased sharing and awareness raising; improving quality of education and training
Social	Improving extension and information access; better planning; improving networks and social interactions (sense of community); increasing membership in formal and non-formal groups
Natural	Alternative uses of nonfarmland; training in crop, soil, and livestock management practices; dredging of rivers and canals to improve drainage
Physical	Building cyclone centers; improving road networks and infrastructure; funding for modern equipment; improving education
Financial	Providing facilities by formal financial institutions; changing policies of financial institutions; inspiring the cooperative system; reducing rate of interest; providing agricultural subsidy

in adapting to changing temperature and rainfall regimes, these options need to be contextualized within the broader choices that farm households make in adjusting to change and how these choices relate back to their livelihood options. Failing to do so will entail a high likelihood that well-intentioned technical adaptation options simply miss the mark as they disregard constraints and alternative options for adaptation.

While the primary rationale for assessing the factors constituting adaptive capacity is to provide the basis for designing more effective adaptation programs at policy and local community levels, we hypothesize that it is only when this understanding is used in tandem with biophysical research to guide the development and evaluation of technical adaptation options that it becomes particularly effective (e.g., rice cropping system adaptations, Gaydon et al 2010). Indeed, the integration of biophysical and social research has been recognized as one of the science frontiers in adaptation research (Howden et al 2007, Resurreccion et al 2008, Meinke et al 2009) and policy support (Cernea 2005).

Integration at the farm household level requires that surveys to analyze adaptive capacity be conducted in a way that also captures data that define farming practices, thereby providing a more realistic configuration of adaptation options for testing with modeling-based scenario analyses (e.g., using cropping systems or farming systems models such as APSIM and IAT, Keating et al 2003 and Lisson et al 2010, respectively). Refining APSIM to enable it to fully capture the dynamics of rice-based cropping systems has been progressing recently in collaboration among IRRI, CSIRO, and the University of Wageningen (Gaydon et al 2009). At the same time, the assessment of adaptive capacity will also help identify which future scenarios are worth investigating and which options, though technically feasible, are less likely to be perceived and accepted by farm households as useful. In effect, IAT modeling outputs link cropping and water management response options back to social attributes, such as labor availability and access to other capitals assessed under the SRL framework. In this way, computer-based scenario analysis can be structured to be more relevant to farm households by merging farming systems modeling with participatory livelihood analysis.

This scale can be complemented by an analysis of adaptive capacity at a broader provincial scale using secondary (e.g., census) data that match the aggregation of crop and water management options at a more generic level. Integration of these two streams within a GIS modeling framework can enable an analysis of the transferability of adaptation options. A critical element in scaling will be the careful development of farming system typologies. As farming systems encapsulate biophysical, economic, and social system attributes, the typologies in themselves essentially represent an integration of social and biophysical research.

Farming systems research to select and evaluate farm-level adaptation options

Farm-level adaptation will ultimately revolve around supporting farming households in identifying and implementing appropriate changes to their farming systems in the context of the constraints that they face (e.g., poverty), the resource-use strategies they can follow (e.g., crops, cattle, or off-farm employment), and the assessment of risks that they undertake. A range of farm-level adaptation options exist, which include the following:

- Reducing risks of crop production through supplementary irrigation to minimize the impact of wet-season drought and to extend cropping seasons; supplementary irrigation can be sourced from water harvesting, establishing tube wells, or gaining access to irrigation canals;
- Matching current crop varieties and cropping systems to possible shifts in rainfall and temperature regimes; this is predicated on a better understanding of climate variability and access to reliable seasonal climate forecasts or downscaled climate change projections that are location-specific;
- Diversifying cropping systems into higher-value crops or improving crop productivity, particularly if supplementary irrigation becomes available;
- Diversifying farming systems by integrating more intensive, forage-based livestock production or aquaculture (e.g., in Vietnam, Cambodia, and Bangladesh);
- Developing and disseminating crop varieties that are better adapted to inundation, drought, temperature stress, emerging pests and diseases, and increasing CO_2;
- Developing stronger farm-to-market linkages, with respect to commodities sold by farm households, in relation to providing farm households with better access to inputs and new knowledge;
- Including processing steps at the farm level as well as other measures to generate added value to crops produced (e.g., packaging, fermenting, quality control, and certification); and
- Combining existing farming activities with nonfarm and off-farm activities, such as provision of services, handicrafts, and marketing.

In evaluating any one of these options, researchers are necessarily confronted with the challenge of testing adaptation options under today's climate for some future, uncertain expression of climate change. This means that, perhaps with the exception of very costly Free Air CO_2 Experiments (FACE) that are not easily replicated across a wide range of farmer practices and conditions, many of the listed adaptation techniques are intrinsically untestable by conventional experimental means. As a consequence, testing of adaptation options will necessarily rely on systems simulation modeling to extrapolate farm-level adaptation options into future climate projections.

In addition to determining the impact of climate change variability on whole-of-farm (crop and livestock) response, farming systems modeling will also need to explore trade-offs between crop and livestock production and other sources of rural livelihoods to help inform farm households of which options might be chosen. In order for a scenario analysis of alternative farming practices to be relevant to farm households, participatory approaches should be used to capture and parameterize existing farm practices in the models. Farm households will also need to be given the opportunity to define and select the scenarios to be tested. However, the desirability of scenarios cannot effectively be determined by local decision making if the participants are not aware of the assumptions and problems that are being addressed in the scenarios. Households and their networks must actively support research activities and perceive them to be a possible basis for making decisions for their own future. Ideally, participatory research will enable farm households to engage in public decision making within the community (Singh et al 2010).

The selection and evaluation of potential modifications to farming systems that have been deemed feasible based on modeling outcomes need to be tested under realistic field conditions. Again, this should be done in an on-farm participatory mode and build on the community engagement processes that are conducted as part of social research aimed at assessing adaptive capacity. The preferred adaptation options should ultimately be those that offer immediate benefits to farm households in terms of increased productivity or reduced risk of production under current climatic variability, while at the same time they are likely to continue performing in the future under changing climatic conditions.

A final consideration in relation to the useful application of farming systems research is the need to evaluate farm-level adaptation options in relation to their likelihood of exacerbating greenhouse gas (GHG) emissions. Indeed, building adaptive capacity of farm households in general is predicated on an overall improvement in their livelihood base. More often than not, this will require an increase in the productivity of local farming systems. Higher crop yields and large numbers of livestock will, by necessity, draw on increased levels of inputs as farm intensification increases. This will increase GHG emissions in absolute terms, even if the rate of GHG emissions per unit of output might decrease because of increased input-use efficiency. To minimize the risk of maladaptation (i.e., adaptation that leads to an exacerbation of GHG emissions), the evaluation of farm-level adaptation options should also account for their efficiency in terms of unit use of input factors (e.g., water productivity, nitrogen-use efficiency, and fuel/energy use per unit biomass produced) to ensure that adaptation does not inadvertently lead to future maladaptation.

Issues of scale

Pairing farm household or community-level adaptive capacity assessments with a household-defined scenario analysis using simulation models that have been parameterized with local farming and climate data will maximize the opportunity for the uptake of adaptation options. However, while the inherent location specificity is a key strength at the local level, the challenge remains how to translate options that may work in specific situations into a suite of more generic adaptation strategies that can be converted into more generic policy options, enabling policymakers to address larger administrative areas and reach out to wider target audiences. In fact, although the biophysical sciences have long understood the importance of scale, research regarding issues of scale in the social and institutional sciences has been less explicit (e.g., Gibson et al 2000). However, any progress in adaptation science is predicated on achieving such bridging across scales. In a recent paper that provides the rationale for adaptation science, Meinke et al (2009) have proposed an "adaptation cycle" as a multiscale conceptual framework on which to base a reflective analysis-action continuum that connects science with society in every step of the process. Meinke et al (2009) further argue that, in order to make the science more relevant to the process of adaptation, it is necessary to embed scientific approaches within context-specific, participatory dialogues that match the highly contextual needs of decision-makers to suitable tools. Meeting this ideal explicitly requires the modeling community to engage all players, from local farm households through community, provincial, and, perhaps, national policymaking levels.

Toward an integration framework for adaptation research

Based on the considerations in the preceding sections, an integration framework has been developed to guide future adaptation research, as shown schematically in Figure 1. The right-hand column illustrates the four steps that are required to obtain farm household adaptation options.

The first of the four principal steps consists of conducting case study based analyses of adaptive capacity using farm household self-assessment approaches. While we have previously argued that the SRL is an exceptionally useful means to do this, particularly by considering the constraining and enabling factors for individuals, households, or communities to cope with change, it is conceivable that other methods may also be applicable for this step.

The second step consists of parameterizing the models to a local context. This entails the derivation of location-specific climate projections using downscaling techniques. This can either be achieved through dynamic downscaling or the less onerous method of statistical downscaling (e.g., the m-quantile method, Crimp et al 2010) provided there is access to high-quality, long-term climate records for the case study regions of interest. Model parameterization using local soil and crop parameters and obtaining local practice benchmark and farming rules through surveys and focus group discussions also form part of the second step. Preference in the choice of models should be given to models that provide a high degree of flexibility in realistically coding or entering specific farmer planting and management decision making (e.g., APSIM).

The combination of the adaptive capacity assessment and the model parameterization then enables the third step

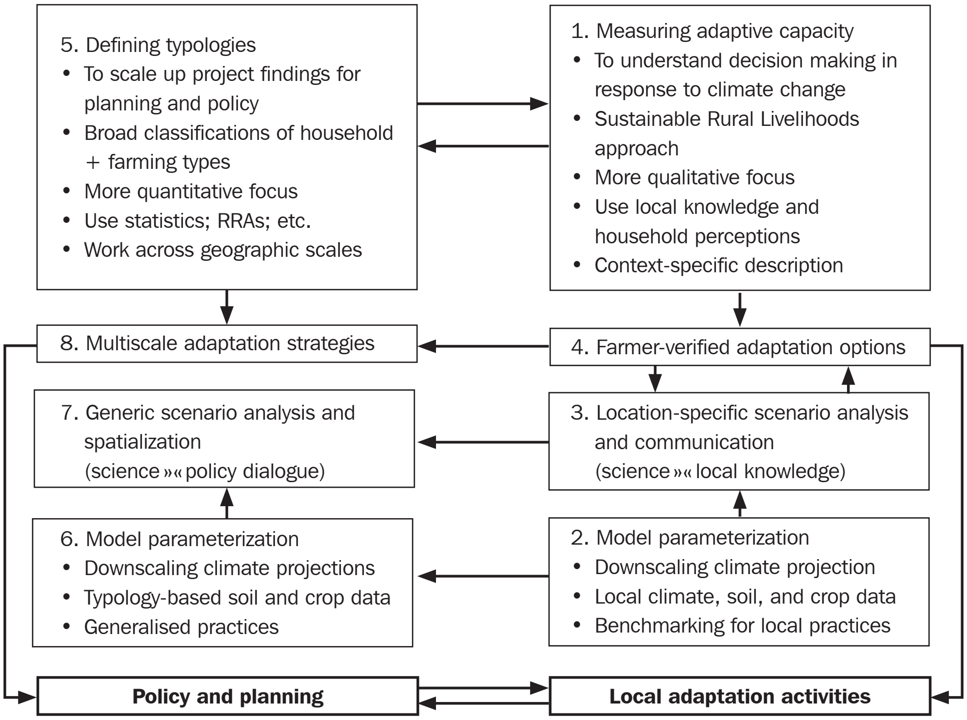

Fig. 1. Integration framework linking adaptive capacity assessment and farming systems modelling to farming system typologies as the pathway to develop multiscale farmer-adaptation strategies.

to be carried out—a scenario analysis using a range of farm household-selected scenarios. This step flows into the fourth step of selecting preferred adaptation options to be tested by farm households on their farms. Ideally, this step would be undertaken in an adaptive learning cycle to incorporate results from the on-farm testing of preferred adaptation options into repeated cycles of steps 3 and 4.

The very strong participatory nature of this combined approach will lead to the identification of adaptation options that will have a high level of farm household ownership and relevance, thus maximizing the prospects for adoption. By supporting this process of developing real alternatives for existing farming systems from perceived options generated by the scenarios, farm households incorporate these options into their decision space and are thus enabled to independently weigh different courses of action (Giampietro 2004).

While it is conceivable that adaptation options arising from step 4 will have a high likelihood of local adoption, upscaling is required to achieve broader dissemination and impact of the approach outlined in the right-hand column of Figure 1. A possible approach to achieve this is shown in the left column of Figure 1, which consists of four additional steps.

In the first instance, in step 5, we propose to use farming situation typologies to generalize from the context-specific results of the adaptive capacity assessment. This might be achieved through the use of secondary statistics and published data in combination with rapid rural appraisals and key informant interviews to construct typologies reflecting the key determinants of the case study sites in step 1. Similar to steps 2 and 3, in steps 6 and 7, the models need to be re-parameterized to reflect more generic farming systems, losing some of the local specificity in exchange for a wider spatial representation. Step 8 results in a suite of adaptation options that are more widely applicable at a range of scales (administrative or geographic). Analogous to the participatory farm household engagement process necessary in steps 3 and 4, for the multiscale adaptation options derived in step 8 to be relevant, these steps need to be carried out in collaboration with policymakers and donor organizations through continuous policy dialogue or workshops. The objective here is not to make policy recommendations but to provide options for policymakers to consider.

The framework described above is presently being applied in a major research project funded by the Australian Centre for International Agricultural Research (ACIAR) in Cambodia, Laos, Bangladesh, and India. The initial results will be forthcoming in mid-2011 and future results of the project will be summarized at http://aciar.gov.au/project/LWR/2008/019.

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Food security, crop health, and global change

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The past decades have seen unprecedented changes occurring globally (Daily et al 1998, Dyson 1999, Liu et al 2007a,b), with dramatic effects on agriculture and the role it has to play in ensuring global food security (Dyson 1999, Smil 2000) as a premier ecosystem service to humanity (MEA 2005). These changes and their consequences will continue: they are related to climate, of course, and also to population growth and globalization with its socioeconomic consequences. These "mega-drivers" of change cascade into a number of effects, including on labor, agricultural land, and agricultural water availability. Natural resources, which are so very strongly connected to agricultural resources, are gravely affected. As a consequence, agriculture has dramatically changed in many areas. In many places in the world, never will agriculture be the same.

New research tools and methods offer directions for applications in the short or longer term. These tools can be operated in a renewed vision of hierarchical relationships within complex systems (Allen and Starr 1982) and include decision-theory Bayesian approaches (e.g., Esker et al 2006), simulation models applied to agricultural systems, (e.g., Penning de Vries 1982), decision-making approaches based on thresholds (Zadoks 1985) that incorporate uncertainty (Rossing 1993), and geographic information systems (Luo et al 1998). Some of these methods have been or are being used in rice research.

Rice research, because it addresses a key global staple food (Zeigler and Barclay 2008), must harness these approaches and tools in order to (1) optimize limited human and funding resources, (2) develop strategies that would maximize the impact of new technologies, and (3) enable technology targeting, which entails consideration of both biological/agronomic and social/economic considerations. These three points are key to success in rice research dealing with climate change and rice diseases.

Climate change and rice diseases

Climate change and plant diseases

The effects of climate change on plant systems are often evaluated without due consideration of plant diseases and other plant pests (Gregory et al 2009). This contrasts very much with the attention paid to climate change consequences on human health (e.g., Balk et al 2006). The scientific community is now mobilizing efforts to address the effects of climate change and plant diseases, however. First, the complexity of the system at hand has to be recognized in order to ask the right questions. The disease tetrahedron (Zadoks and Schein 1979) can be influenced by climate change and variability in many ways. Several layers of hierarchy, from genomes to ecosystems, and the corresponding complexity of their relationships (Scherm and van Bruggen 1994, Coakley et al 1999, Chakraborty et al 2000, 2003, Garrett et al 2006, 2009) are to be considered. One critical element for future research, therefore, is that it will have to be holistic, addressing the behavior of entire systems in their responses and possible feedback to climate change and variability, rather than addressing individual components of a system at a time (Teng and Savary 1992). Reductionist approaches to this question (Garrett et al 2010), while being very useful in documenting individual aspects, tend to downplay the critical role of interactions among system components. One specific element that seems to have received little attention from climate change scientists so far is that plant diseases may also be seen as markers of climate change (Garrett et al 2010); this will be addressed again briefly for rice diseases.

Surprisingly, much of the current effort has dealt with the dynamics of plant diseases in response to climate change, but very little has dealt with the ultimate consequences these have on the raison d'être of plant pathology: the crop losses that diseases can cause to cultivated plants (Oerke 2006, Pardey and Woods 2008). This, of course, is critical in the case of rice (Zeigler and Savary 2010). Although climate change and its consequences on plant diseases may have dramatic, sometimes catastrophic, effects on natural ecosystems (Garrett et al 2006, Jeger and Pautasso 2008), failing to address this outcome would render studies on climate change-related risks rather academic from an agricultural point of view. This is a critical element, which is briefly addressed below.

The critical case rice diseases represent

Aside from the importance of rice as a critical global staple food crop—some 3 billion human beings depend on that single crop—rice represents a critical case for climate change research to (1) have impact, (2) develop adaptation strategies, and (3) build a convincing scientific case. The third of these points can briefly be addressed first. Rice, globally, is host to a tremendous range of plant pathogens (Ou 1987). This, in reality, represents a fairly representative segment of that part of biodiversity that has played a significant role in the evolution of plants as we know them today, whether cultivated or not: plant pathogens (Wilson

1992). Further, rice probably represents the crop that is being cultivated in the largest range of agroclimatic environments and in a tremendous range of socioeconomic contexts (Greenland 1997). There are therefore a number of fundamental scientific questions that rice and its many diseases, as a model system, raise in the context of climate change research: a) how to develop a research framework that enables addressing the interplay of a range of system components that truly make it complex, and where attention is not paid to biophysical components only but to socioeconomic components as well (see, for example, Eakin and Luers 2006), including policies; b) how to develop a research strategy that captures the diversity of production systems and socioeconomic fabric; c) what the entry points are to possible management of this system; and d) how to incorporate specified levels of uncertainty (Savary et al 2010) in the inputs to the system (including, but not limited to, climate variability).

The basic notion of an ecological niche also applies to plant pathogens (McRoberts et al 2003): empty niches in a biological system tend to be rapidly filled. This is the principle that leads to crop health syndromes (i.e., combination of plant harmful organisms, including pathogens) in rice being diverse and associated with diverse production situations (Savary et al 2000a). Community ecology, a field of research in its own right (e.g., Gilman et al 2010), may find in rice diseases, their syndromes, and the functional guilds they represent (see below) a key, well-documented model system. Another question, then, is: What will be the crop health syndromes of rice in the future, given climate change and variability? This, of course, incorporates questions regarding the future role of "new," "emergent," and invasive plant pathogens—Are they to play the role of keystone species in such syndromes? Several of such diseases, including false smut (Reddy et al 2010) and spikelet rot (Huang et al 2010a,b), are becoming the focus of increasing attention. One important point about these (panicle and grain) diseases is their association with the production of toxins, leading to renewed questions on the nature of what a keystone species should be: a component in the behavior and the dynamics of an entire guild of rice pathogens in a syndrome or a key element of crop loss (which includes the reduction of harvest quality, in addition to that of harvested yield)—i.e., of food security as well as of food safety. The developing world is entitled to food safety as much as the developed world is, even though it is placing so much emphasis on the latter rather than on the former.

Returning to the point of climate change markers, it is useful to return to earlier studies in which contrast was made between diseases afflicting the "poor" as opposed to those affecting the "rich" rice farmer (Zadoks and Schein 1979). A case must be made on brown spot of rice, a disease that has recently been quantitatively documented to strongly increase with water shortage (Savary et al 2005), along with a number of soil- and nutrient-related factors (Ou 1987), and for which research needs to (and can) make progress to deliver sustainable management solutions (Reddy et al 2010).

The first two points above follow the third one: impact will be derived from the development of management strategies, primarily based on the wise deployment of scarce resistance genes, where they are needed, and when they have the largest impact in managing diseases and reducing crop losses; these represent adaptation strategies to climate change and, more generally, global change in a still growing world population, for which economic rules may change, locally to globally.

What it will take to address this

Rice research, through IRRI and its many partners, including other CGIAR centers, national research institutions, and advanced research organizations, can harness a range of approaches and tools that "Rice Disease–Climate (and Global) Change" represent.

One first element is that data at the farmers' field level, pertaining to diseases but also to insect and weed injuries, as well as field-specific elements on production situations, have been collected and assembled over the decades (Savary et al 2000a). These may provide a first approach to analyzing the relationships between disease syndromes and production situations (Savary et al 2006), as well as addressing this relationship in a hierarchy of drivers of agricultural changes and analyzing the likelihood of syndromes expanding (or reducing) in scenario analyses (Savary et al 2010).

A second element is that a fair, if not complete, amount of information on the levels of yield losses associated with varying levels of injuries to diseases (as well as to insects and weeds) is available (Savary et al 2000b) from a series of linked field experiments in which factors driving the attainable yield (Zadoks 1985) have been manipulated: yield losses occurring at attainable yield ranging from 2 to 10 t ha^{-1} are thus available, enabling a statistical model to be developed:

$$L = f\ (Ya, I),$$

where L is yield loss, Ya is attainable yield, and I is injury (caused by an individual disease or a combination of yield-reducing organisms).

Third, RICEPEST, a generic, simple, production situation-specific simulation model has been developed and heavily tested in China, the Philippines, and India (Willocquet et al 2004). This model involves a limited series of generic damage mechanisms (Ayres 1981) and enables, in a much more elegant way than a statistical model, assessment of yield losses caused by diseases (or pests, in general), which share the same damage mechanisms—one thus can look at rice (and crop) pests as elements of guilds of yield-reducing organisms. Importantly, RICEPEST (1) also enables one to quantify yield gains generated by management strategies (existing, in the process of being developed, or required, given the levels of losses observed), rendering the model a tool that can be used for research prioritization; and (2) has a structure that enables linkage with other algorithms, notably GIS tools.

Fourth, efforts are currently under way to develop EPIRICE (Savary, Nelson, Willocquet, Hijmans, unpublished), a generic, universal simulation model that will enable simulating epidemics that occur at a range of hierarchy levels, from the fraction of a leaf that can be infected (leaf blast, brown spot) to an entire leaf (bacterial blight) to a whole tiller (sheath blight) and to the entire plant (rice tungro disease). EPIRICE is based on the early structure developed by Zadoks (1971), with a few modifications, and a limited series of coupling points enabling climate (canopy moisture, especially; Huber and Gillespie 1992) and other production situation elements to be accounted for. EPIRICE has successfully been coupled with weather data and crop establishment dates, enabling the modeling of potential (i.e., unmanaged) epidemics to be globally mapped.

As far as crop health is concerned, however, there is no substitute to ground truth, that is, the careful assessment of injuries caused by diseases, animal pests, and weeds in farmers' fields. Only when this information is available and updated can we assess our models, the impacts of change, and the options for management. IRRI conducts research on that basis. Our field-based information requires constant updating, especially where production situations are fast evolving, and that is the case in many places in Asia. This is an ongoing challenge rice scientists have to face: without "eyes in the fields," our work may well soon become irrelevant, with dramatic consequences, given the current research-application-transfer time frame (Pardey 2006).

Conclusions

The next 10–20 years will be crucial: during this time, demographic transition will lead to population increasing and progressively stabilizing, while resources for agriculture will become more scarce. These years will therefore see maximal human populations meet challenging food supply, which must remain sustainable. These years will be, in the positive sense of the term, challenging years for agricultural scientists: societies worldwide will very likely reward, or criticize, them for their accomplishments.

In this short text, we focused on food security from the rice production standpoint and on plant protection for rice in connection with agronomy. A sample of new techniques that plant protection specialists are now using has briefly been described. These include (1) large-scale surveys in farmers' fields; (2) their statistical analysis with new, modern methods; (3) simulation modeling of multiple disease dynamics; (4) analysis and modeling of crop losses due to diseases, weeds, and animal pests; and (5) the linkage of a body of information to geographic information systems. All these methods are generic—they do not belong to plant protection in isolation but call upon skills in agrophysiology, statistics, modeling, GIS, genetics and breeding, and, more generally, agronomic understanding.

As a field of science for application in agriculture, plant protection is probably one of the best examples to show that, if it is to remain relevant in the coming two decades and beyond, it must open itself to other disciplinary expertise. Of course, specific knowledge of, say, diseases and pathogens will remain a critical element for future "plant doctors." Yet, a similar reasoning applies to all the fields of agricultural training, research, and application: the relevance of agricultural professionals will depend on both their scientific roots—the classical disciplinary expertise—and a good knowledge of agricultural systems, which, inevitably, will have to evolve to remain sustainable. This latter knowledge will be key for agricultural scientists and professionals to adapt to a changing world. It also is an opportunity to attract young professionals to an array of skills and roles.

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Modeling approaches for assessing adaptation strategies in rice germplasm development to cope with climate change

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This study explored the potential pathways of rice germplasm development as a means to adapt to climate change. This assessment was based on the crop model ORYZA2000 that comprises cultivar-specific response curves for both optimum growth temperature and panicle tolerance. These crop parameters have been calibrated and validated for cultivars IR72 and IR64 and we have shifted the respective temperature response curves to assess the impacts of hypothetical improvements in germplasm. The climate data to drive the model were derived from historical weather data from the Experiment Station of the International Rice Research Institute, Philippines. We have then manipulated the climate data by increasing temperature by 1 to 6 ºC. Likewise, we have also simulated the impact of higher CO_2 (1.5x, 2.0x, and 2.5x current CO_2). Without a temperature increase, higher CO_2 resulted in potential grain yield gains of 23–32% for 1.5x CO_2, 37–49% for 2x CO_2, and 45–60% for 2.5x CO_2, respectively. However, an increase in temperature decreased yields; the decrease rates of grain yields in per ºC increase of daily mean air temperature varied between 8% and 13%, and the rates were larger with higher CO_2 and also differed among seasons (dry > wet season) and cultivars (IR64 > IR72). However, our modeling results indicate that, under elevated CO_2 and increased daily mean air temperature, shifting the optimum temperature alongside a temperature increase can improve potential grain yield only if the increments of daily mean air temperature are less than 3 ºC in 1.5x CO_2 and 5 ºC in 2.5x CO_2. The shifting of panicle heat tolerance of increased air temperature ensures that potential grain yields are 3–47% higher than current levels. The combination of the abovementioned two germplasm development strategies can achieve higher potential grain yield but it can lower the net achievement resulting from an improvement of panicle heat tolerance. Through this study, the best strategy found in germplasm development to cope with increasing air temperature is to improve panicle heat tolerance without worrying about growth temperature.

Rice is a staple food for about half of the world's population. The impacts of climate change on rice production have been elucidated by many studies (Masutomi et al 2009, Krishnan et al 2007, Sasaki et al 2007, Sakai et al 2006, Yang et al 2006, Baker 2004, 2000, Matthews et al 1995). In the process of progressing climate change, elevated atmospheric CO_2 concentrations render benefits on plant growth and yield (Tubiello et al 2007, Yang et al 2006, Garcia et al 1998, Drake et al 1997, Morison 1985). On the other hand, increasing air temperature will reduce the productivity of crops grown near the limits of their maximum temperature tolerance (Ferris et al 1998, Prasad et al 2006). Due to these diverging effects caused by climate change, recent estimates on the changes in rice production also vary within a very broad range—from –13% to +27% for the 100-year time horizon in which atmospheric CO_2 is expected to double (Masutomi et al 2009, Baker 2000, Mathews et al 1995). In addition to possible offsets, elevated CO_2 concentration and increasing air temperature also show complex interactions that further obscure forecasting impacts.

The development of germplasm could play a crucial role in coping with hotter environments and a CO_2-rich atmosphere (Wassmann and Dobermann 2007). However, the most effective breeding strategies or mechanisms to capture the positive effects of CO_2 elevation and minimize the negative effects of increasing temperature are still under debate.

This study deploys modeling approaches for testing three adaptation strategies in germplasm development. The point of entry for our study is that crop models such as ORYZA2000 have built-in algorithms to describe the effects of higher temperature and CO_2. In turn, these algorithms can be manipulated to emulate a hypothetical improvement in specific plant traits.

Materials and methods

Model simulations

The ORYZA2000 model has been developed as a rice growth simulation model for potential and water-limited conditions and has been expanded to nitrogen-limited conditions (Bouman et al 2001). The model is driven by daily weather information on rainfall, maximum and minimum temperatures, and solar radiation (Bouman et al 2001).

All simulations conducted in this study assumed that rice grows under conditions with no water and nitrogen limitations and no yield reductions caused by pests and diseases. Simulations were carried out for two varieties, IR72 and IR64, using validated crop parameters of either variety (Bouman and van Laar 2006, Boling et al 2007). Historical weather data of 29 years from the IRRI rice experiment field at Los Baños, Philippines, were used to drive model simulations for the wet- and dry-season crops.

The climate change scenarios (for around year 2100) encompassed several assumptions:

1) Atmospheric CO_2 concentrations were supposed to have three types of changes: 1.5, 2.0, and 2.5 times that of the current level.
2) Weather data of 29 years have been used to simulate baseline yields and modified yield under three CO_2 concentrations.
3) Increments of daily mean air temperature (DMAT) staggered in six categories (1–6 ºC) were superimposed on the historical weather data.

Three possible breeding strategies were evaluated in this simulation study:

1) Shifting optimum temperature for crop growth corresponding to respective increments in DMAT (Fig. 1A).
2) Shifting temperature thresholds for panicle tolerance corresponding to respective increments in DMAT (Fig. 1B).
3) A combination of both shifts.

Table 1 presents the details of the simulation scenarios. Other factors such as transplanting dates and seedling age were identical for all simulations.

Statistical analysis

The distribution and variation of potential grain yield in 29 years were analyzed by the free software R. It was also employed to graph the results of statistical analysis.

Results

Figures 2 to 5 illustrate the simulated potential grain yields under different scenarios. In comparison with the baseline, elevated CO_2 significantly increased potential grain yield. The increase in DMAT lowered potential grain yield. The elevated CO_2 and increased DMAT enlarged the variations in potential grain yield, especially in the dry season. All adaptation strategies did not completely eliminate the reductions brought by increasing DMAT on potential grain yield and the increases resulting from elevated CO_2 were offset in different magnitudes.

The adaptation by shifting the optimum temperature of crop growth to synchronize with increments in DMAT benefited rice production if the increment in DMAT was less than the tipping point at which potential grain yield became lower than the baseline. The temperature increments to reach the tipping point were 3–5 ºC. They were higher in the dry season than in

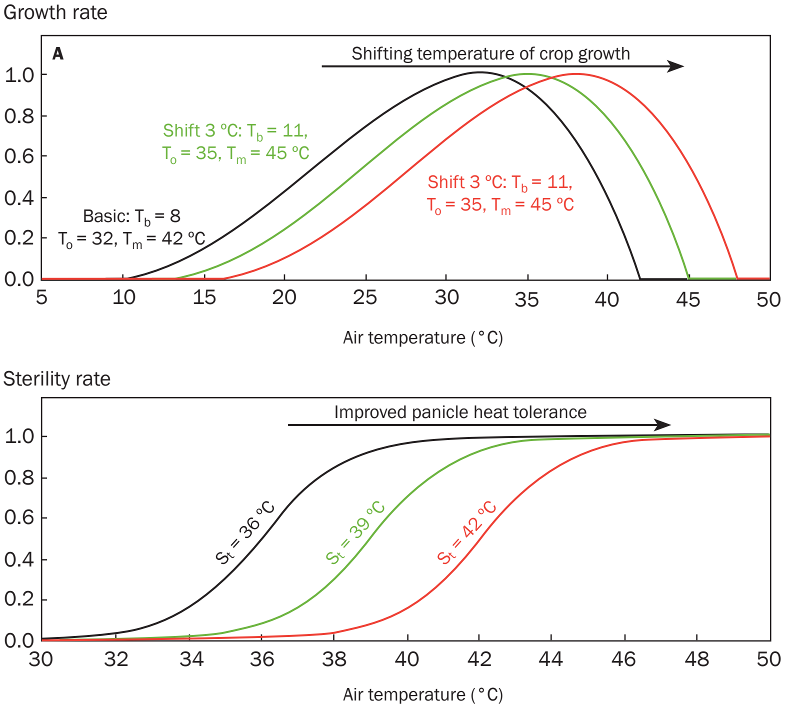

Fig. 1. Assumed germplasm development to cope with increasing air temperature. T_b, T_o, and T_m are the minimum, optimal, and maximum air temperature of rice growth. The rice stops growing while air temperature is lower than the T_b or higher than the T_m, and it reaches maximum growth if air temperature equals T_o. S_t is the threshold air temperature of spikelet sterility at which sterility rate reaches 50%.

Table 1. Simulation matrix for combining different CO_2 and temperature levels with different adaptation strategies in germplasm development:

- **Different CO_2 levels encompass current CO_2 levels (…') as well as 1.5x (…&), 2x (…*), and 2.5x (…#) current CO_2 levels.**
- **Each CO_2 level is considered with seven different temperature levels—i.e., T0 and increments in daily mean air temperature of 1 °C (T1) to 6 °C (T6), respectively.**
- **NA indicates "no adaptation" scenarios under respective CO_2 levels and T0 including baseline (BL) scenario under current CO_2.**
- **O1 and O2 to O6 indicate adaptation of rice germplasm through shifts in the optimum temperatures of rice cultivars by 1 and 2 to 6 °C, respectively.**
- **P1 and P2 to P6 indicate adaptation of rice germplasm through shifts in the threshold temperatures for panicle tolerance of rice cultivars by 1 and 2 to 6 °C, respectively.**
- **OP1 and OP2 to OP6 indicate adaptation of rice germplasm through shifts in both optimum and threshold temperatures by 1 and 2 to 6 °C, respectively.**

	Current CO_2							1.5x CO_2	2.0x CO_2	2.5x CO_2
	T0	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T0…T6**	**T0…T6**	**T0…T6**
NA	**BL (NA')**							NA&	NA*	NA#
O1		O1'						O1&	O1*	O1#
O2			O2'					O2&	O2*	O2#
O3				O3'				O3&	O3*	O3#
O4					O4'			O4&	O4*	O4#
O5						O5'		O5&	O5*	O5#
O6							O6'	O6&	O6*	O6#
P1		P1'						P1&	P1*	P1#
P2			P2'					P2&	P2*	P2#
P3				P3'				P3&	P3*	P3#
P4					P4'			P4&	P4*	P4#
P5						P5'		P5&	P5*	P5#
P6							P6'	P6&	P6*	P6#
OP1		OP1'						OP1&	OP1*	OP1#
OP2			OP2'					OP2&	OP2*	OP2#
OP3				OP3'				OP3&	OP3*	OP3#
OP4					OP4'			OP4&	OP4*	OP4#
OP5						OP5'		OP5&	OP5*	OP5#
OP6							OP6'	OP6&	OP6*	OP6#

the wet season and also higher for variety IR72 than for IR64. The temperature towards the tipping point increased in parallel to the increase in CO_2 concentration.

In addition to changes in average yield, the adaptation scenarios also showed strong differences in variations of potential grain yield. Generally, rice production was not effectively improved if germplasm was improved by adjusting the temperature optima. In comparison with the baseline, this improvement resulted in a change in potential grain yield from –59% to 47%, which depended on CO_2 and the increase in DMAT. The positive effects of elevated CO_2 on potential grain yield were not reversed, and the negative effects of increasing temperature were not buffered by this adaptation, especially at high-temperature conditions.

The adaptation by simultaneously improving panicle heat tolerance in the same degree of increments in DMAT significantly elevated rice production. The potential grain yields were 3–47% higher than the baseline. The positive outcome still existed even if DMAT increased by 6 °C of the ceiling level. In comparison with potential grain yields under elevated CO_2 alone, the adaptation effectively reduced the deductions of increased DMAT to the increases derived from elevated CO_2. This adaptation had different responses to increased DMAT in the dry and wet seasons. In the dry season, potential grain yields slowly declined when the increments in DMAT were less than 3 °C, but they were almost the same or even had a slight increase when DMAT increases were more than 3 °C. In the wet season, grain yields decreased slowly and constantly with the increase

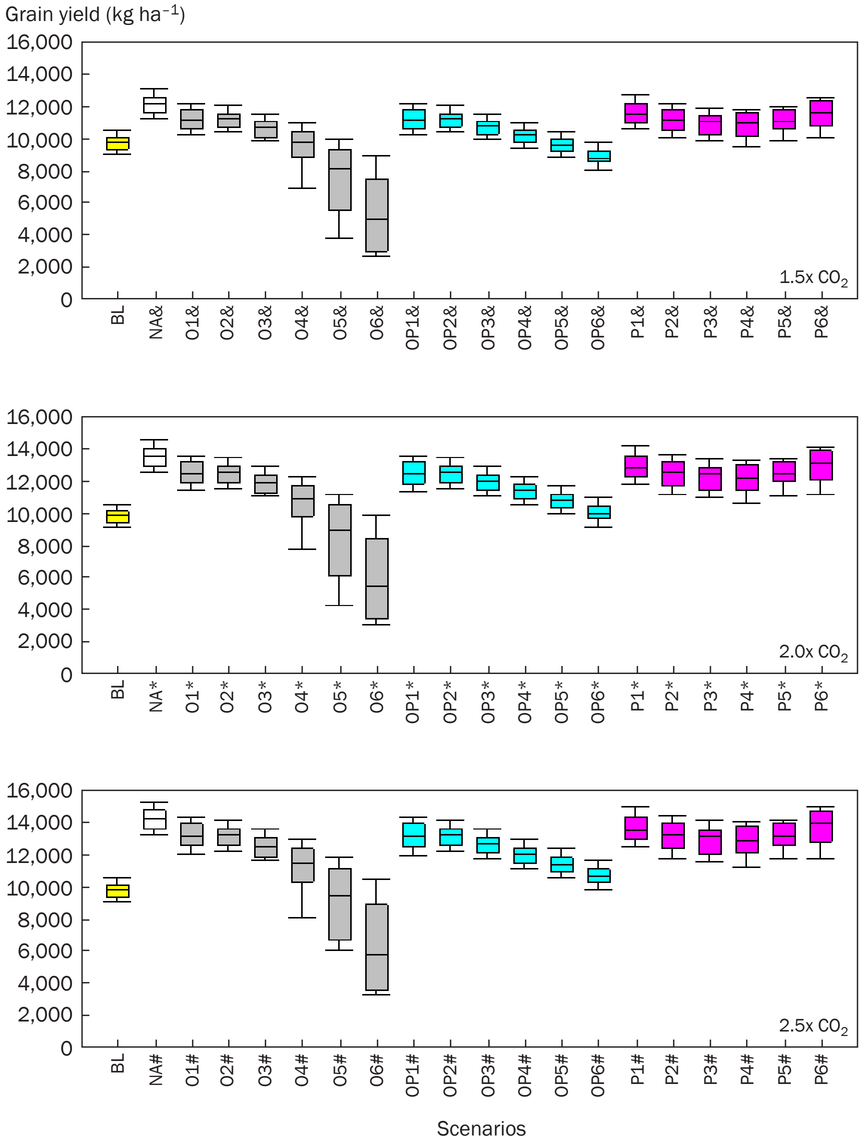

Fig. 2. The effects of adaptations on potential grain yield of IR72 in the dry season. The definitions of scenarios are in Table 1.

in DMAT. The same context of improvement in panicle heat tolerance as that of increments in DMAT buffered the negative effects of increasing DMAT on potential grain yield more effectively in the dry season than in the wet season.

Conclusions

The combined adaptation of the two strategies had better effects on potential grain yield than the first strategy, but it was not as good as the second strategy. The potential grain yield consistently decreased to values lower than the baseline as DMAT increased. The reduction rate of potential grain yield per 1 °C rise in DMAT was higher in IR64 than in IR72. These reductions were also stronger in the wet season than in the dry season.

In summary, the tested adaptation strategies in germplasm development increased potential grain yield if the DMAT increase was less than 3 °C. The improvement in panicle heat tolerance was the most effective. If the improvement in panicle heat tolerance could catch up with the increase in DMAT, the positive achievement in potential grain yield resulting from elevated CO_2 could be effectively reserved. For achievable germplasm development, rice breeding for hot environments should focus on improving panicle heat tolerance but not on the other two tested adaptations.

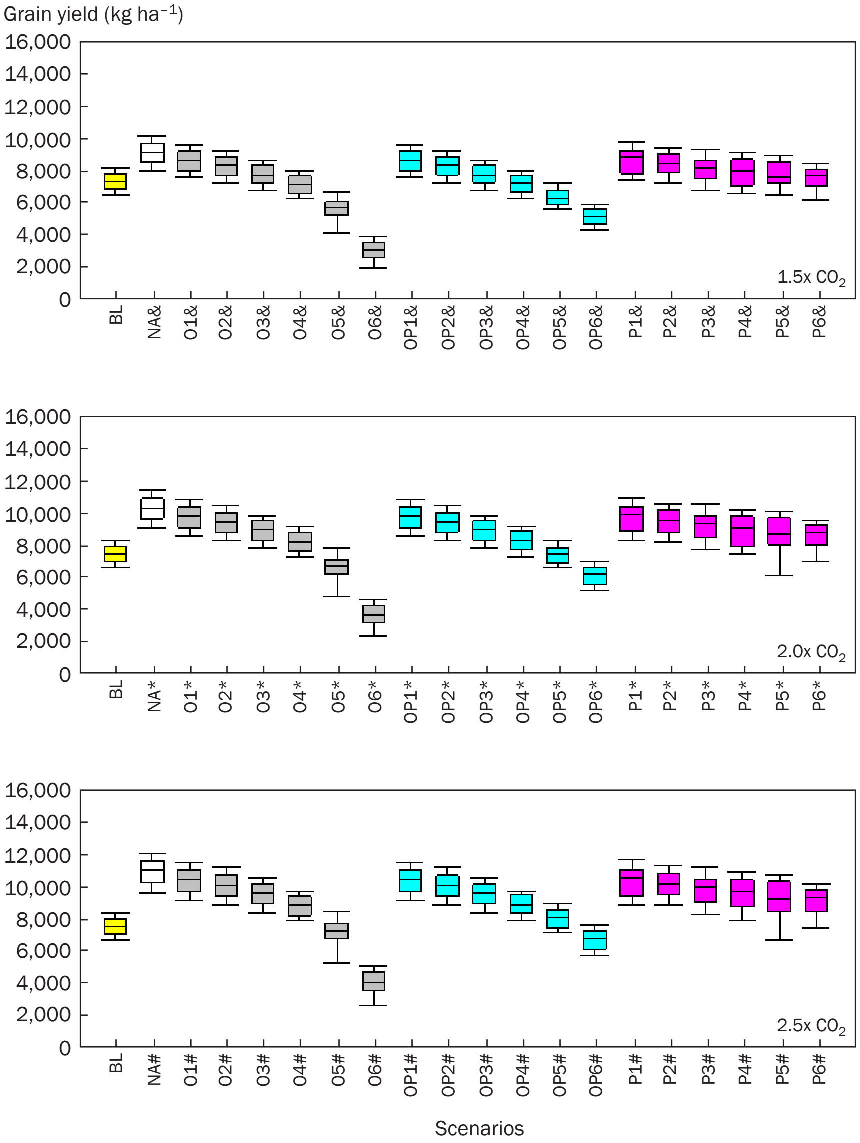

Fig. 3. The effects of adaptations on potential grain yield of IR72 in the wet season. The definitions of scenarios are in Table 1.

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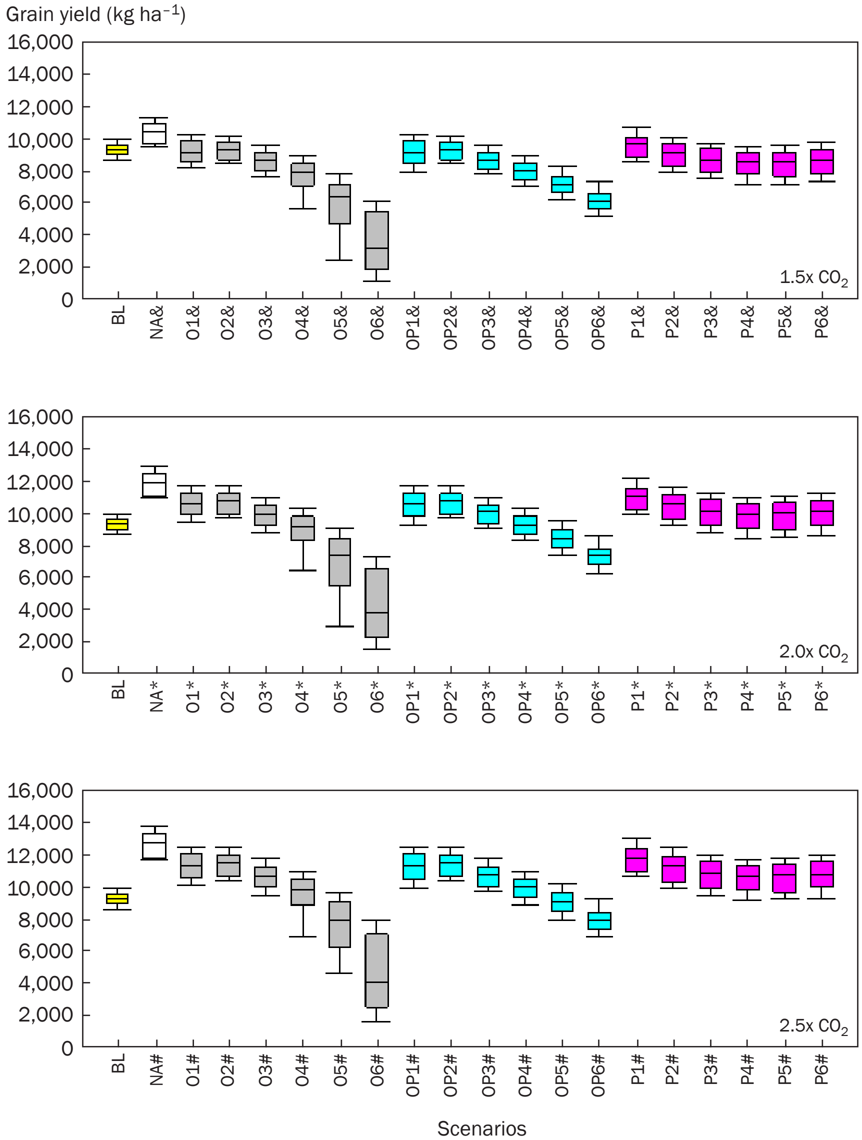

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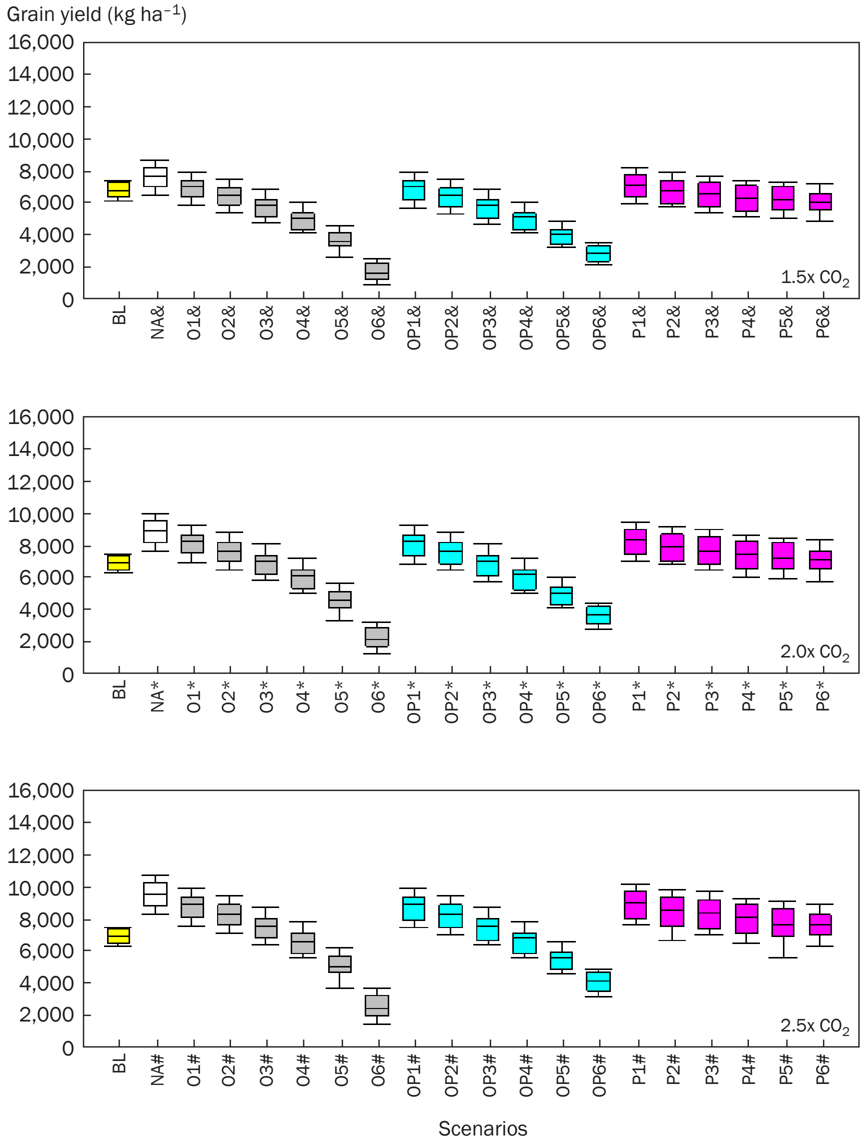

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Implementing the Clean Development Mechanism in the land use sector: status and prospects

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The modalities on how to foster mitigation efforts in developing countries have been at the core of all Conference of Parties (COPs) negotiations of the United Nations Framework Convention on Climate Change (UNFCCC). As early as 1997, the Clean Development Mechanism (CDM) was introduced for transferring funds from Annex I (industrialized) countries to Non-Annex I (developing) countries in exchange for certified emission reductions (CERs). CDM is now a well-established instrument to fund mitigation projects such as biomass and biogas technologies, but the eligibility of projects reducing *in situ* emissions from land use such as methane emissions from rice remains intricate. The recent international debate indicates an emerging consensus to include greenhouse gas (GHG) sources from land-use systems. This development follows an earlier agreement on REDD (reducing emissions from deforestation and forest degradation), which has been officially recognized in the Copenhagen Accord. This more inclusive concept is now often perceived as “REDD-plus-plus” that would, in principle, allow mitigation projects in land-use systems such as crop land. However, in the first instance, any CDM project on methane emissions from rice fields would need an approved “methodology” for this specific source. While there are some prospects that this might happen in the near future, the feasibility of such CDM projects will largely depend on the stipulations of the approved methodology. It remains to be seen how the rather rigorous criteria for issuing CERs can be reconciled with the spatial and temporal variations that are innate to a GHG source such as rice fields. Other mechanisms for financing mitigation projects might be more suitable for mitigation projects targeting changes in land use. Such funding could come from the newly established Copenhagen Green Climate Fund as well as from voluntary commitments (typically pertaining to countries that have not ratified the Kyoto Protocol). Despite these uncertainties, the development of mitigation technologies should be continued to provide available options with varying project scale and verification requirements.

Right from the onset of the climate change debate in the early 1990s, it was generally recognized that agriculture will be one of the most affected sectors and that agriculture should do its share to reduce emissions. Moreover, there has been—and still is—a broad consensus that developing countries will need support from the developed world due to insufficient resources to adjust to climate change and increase resource-use efficiencies for mitigation. In turn, the developed countries (referred to as Annex 1 countries under the Kyoto Protocol) have continuously pledged support for the developing countries (referred to as Non-Annex I countries) in both adaptation and mitigation.

International agreements on mitigation in the agricultural sector

The modalities on how to foster mitigation efforts have been at the core of all Conference of Parties (COPs) and other climate negotiations among developed and developing countries. In principle, the different funding pathways for north/south interaction in mitigation projects can be subdivided as follows:

1. Clean Development Mechanism (CDM). CDM is one of the flexible funding mechanisms introduced in the Kyoto Protocol that have been designed to transfer funds from Annex I to Non-Annex I countries in exchange for certified emission reductions (CERs).
2. An international fund for mitigation projects. This type of funding would be in line with the funding of adaptation as outlined in the Bali road map and the Copenhagen Accord. As a prerequisite for participation, developed countries are obliged to submit plans for nationally appropriate mitigation actions (NAMA). However, the nature of the national commitments embedded in NAMAs is still under debate; NAMAs could be unilateral, conditional, or credit-generating. So far, the extent to which this instrument will lead to genuine emission reductions remains to be seen.
3. Voluntary commitments. This type of funding is currently given by countries that have not ratified the Kyoto Protocol. For instance, in the U.S., pressures for stronger climate change action continue to mount despite the government’s consistent rejection of the Kyoto Protocol. Obviously, this type of funding entails advantages in terms of flexibility, but its voluntary nature will always carry the risk of abrupt termination.

The specifics of the Kyoto Protocol and CDM regarding the land-use sector

The Kyoto Protocol, adopted at the 3rd Conference of Parties (COP3) in 1997, recognized land use and land-use change as a source of greenhouse gas (GHG) emissions as well as a potential source of C removals. The Kyoto Protocol also introduced innovative funding mechanisms, such as the CDM, for supporting mitigation projects in Non-Annex I countries. On the other hand, the Kyoto Protocol was very vague in defining the role of agriculture within the CDM process. It took the parties until COP7 (2001, in Marrakesh, Morocco) to specify these regulations. The Marrakesh Accord stipulated the following modalities and procedures pertaining to CDM (decision 17/CP 7):

- The eligibility of land use, land-use change, and forestry project activities under the CDM is limited to afforestation and reforestation.
- The treatment of land use, land-use change, and forestry project activities under CDM in future commitment periods shall be decided as part of the negotiations on the second commitment period (post-2012 climate change regime).

These regulations of the Marrakesh Accord reflect a subdivision within each of the two sectors:

Sector	Forestry	Agriculture
Eligible	Afforestation and reforestation	Animal waste treatment (biogas, etc.), biomass energy (e.g., rice husk combustion for electricity generation)
Excluded	Deforestation	*In situ* emissions from land use, including rice production

In the meantime, however, these regulations have been challenged in the negotiations of the ensuing COPs. The exclusion of deforestation projects from CDM has been criticized by several governments and NGOs as an impediment to sustainable development of the remaining forestry resources. The Coalition of Rainforest Nations has proposed a mechanism called reducing emissions from deforestation and forest degradation (REDD) as a means to use market/financial incentives for GHG mitigation. In the course of public debate, this has been expanded to the concept of "REDD-plus" aiming at co-benefits such as biodiversity conservation and poverty alleviation. As an apparent success of this initiative, the Copenhagen Accord in December 2009 recognized the crucial role of reducing emissions from deforestation and forest degradation and the need to provide positive incentives to such actions through the immediate establishment of a mechanism that includes REDD-plus.

In spite of its perceived potential in the post-2012 climate change regime, the forestry sector plays only a marginal role in the CDM process at present. As of June 2010, the regularly updated inventory of CDM projects (see http://cd4cdm.org/) lists 56 forestry projects in the CDM pipeline (corresponding to 1% of all projects currently in the pipeline) and zero projects with CERs issued. The CERs are often referred to as "carbon credits" issued by the CDM Executive Board of the United Nations Framework Convention on Climate Change (UNFCCC). The analysis of CDM projects in the agricultural sector requires more elaboration. The project type "agriculture" is listed in Table 1 with zero projects and CERs. However, the project types "biomass energy" and "methane avoidance" are mainly composed of agriculture-based projects such as production of biofuel crops and biogas technology in combination with animal husbandry, respectively. Collectively, these two project types account for 25% of all CDM projects in the pipeline and 10% of CERs to be issued by 2010. With regard to successfully implemented projects, the figures in the table reflect a steady rise in the dimension of these projects in recent years; these two categories had a similar share in total number, but they accounted for only 5% of CERs already issued.

In contrast to biomass and biogas technologies, the eligibility of reducing *in situ* emissions from land use such as methane from rice remains intricate. The Marrakesh Accord passed the final decision onto future COPs as part of the negotiations on the second commitment period. In principle, this means that the question would have to be clarified any time soon since this period will begin in 2013. The disappointing outcome of COP15, however, has raised doubts whether this can really be achieved prior to the next commitment period.

The decisions expressed against land-use projects in earlier COPs were mainly driven by skepticism against the longevity of efforts to increase carbon sinks in agricultural systems (e.g., zero tillage). At that point, projects targeting the reduction of sources from land use have not been really thought about. In turn, the interpretation of these regulations could be either

- in a literal sense, which would exclude CDM projects on methane reduction from rice production; or
- in a contextual sense, which would allow such projects in line with projects on biomass and biogas technologies.

Moreover, even the exclusion of agricultural sinks will have to be revisited because of technologies that have not been considered in the earlier COP discussions. For instance, a "biochar" proposal submitted to the COP14 in Poznan, Poland (2008), has been accepted by the UNFCCC for the "dialogue" on the post-2012 climate change regime. This broader concept of CDM projects, including GHG sources and sinks of land-use systems, is now often called "REDD-plus-plus."

The perception of a more inclusive role of land-use systems in the CDM process is also reflected in recent decisions by the UNFCCC body, which is responsible for approving CDM methodologies. An approved methodology for quantifying emission reductions is the prerequisite for any CDM project. In turn, CDM projects on emission reductions in rice production are presently unattainable because there is no approved methodology. However, a proposal for a small-scale methodology titled "Reduction of methane emissions by switching from transplanted to direct-seeded rice practice with adjusted water management" has recently been submitted to the UNFCCC (http://cdm.unfccc.int/UserManagement/FileStorage/4BTFS58C2AXGMPIVDOJEL3K1Y0UWRN). Although the approval process is still pending, it should be noted that UNFCCC has embarked on a review process of this proposal without questioning the eligibility of a CDM method dealing with emission reductions in rice fields. An approved methodology could be deemed a breakthrough for facilitating future CDM projects in rice, although the feasibility of such projects will depend largely on the stipulations coming out of this review process such as the required frequency and duration of field observations for obtaining CERs.

Challenges for implementing CDM projects in the land-use sector

Assuming that the legal framework may in the future allow CDM projects in the land-use sector, their implementation will face several challenges (Reilly and Asadoorian 2007). In contrast to other sectors such as industry, transport etc., the computation of emission rates is attached to very large uncertainties. Land-use systems show enormous variability in terms of space and time, which is in part due to natural factors (namely soil properties and climate) as well as distinct crop management practices (Garcia-Oliva and Masera 2004). Thus, thorough principles and protocols for validation and verification of emission reductions will become critical prerequisites for CDM projects in the land use sector. In the context of CDM, the term "validation" denotes the planning of a project according to a set of criteria (CDM Executive Board 2008) to

- define a baseline following a methodology approved by UNFCCC and by adjusting for "leakages" (subsequent emissions outside of the project boundaries caused by project activities),
- ensure additionality of the project, and
- provide for consistent project operation and monitoring.

Verification is the independent review and ex post determination of monitored emission reductions that have occurred as a result of a registered CDM project activity during the verification period (UNEP 2008). With regard to emission calculations, these can broadly be divided into two categories (UNEP 2008):

1. Emission calculations that will be monitored and recalculated ex post—i.e., the project design document contains only an estimate that will not be the basis for the final CERs.
2. Emission calculations that are determined ex ante and remain fixed during the crediting period of the project.

In June 2007, the CDM Executive Board approved a "methodological tool" called "Estimation of direct nitrous oxide emission from nitrogen fertilization" (CDM Executive Board 2007). However, this document explicitly excludes "flooding irrigation or any flood that has occurred within a period of 3 months from date of fertilization." Thus, nitrous oxide emissions from rice fields are not covered by this tool; neither have methane emissions been addressed by any "methodological tool" up to date.

One of the critical questions for possible CDM projects in the land-use sector is the setting of baselines (Kaku and Ikeguchi 2008). A CDM baseline is defined as "the scenario that reasonably represents the anthropogenic emissions by sources of greenhouse gases that would occur in the absence of the proposed project activity". While this definition sounds like a mere technicality, the implication of different baseline settings can be enormous; it can, in fact, become a decisive feature in making a CDM project profitable or unrealistic. In particular, the baseline concept of a CDM project penalizes good practices prior to the project. In the case of rice production, farmers who have already adopted alternate wetting and drying could hardly gain any carbon credits because their baseline is already at a low level of GHG emissions.

Conclusions

CDM projects have to meet a series of criteria to be measurable, transparent, and verifiable. Meeting these criteria is especially challenging for the land-use sector in general and for rice production systems in particular.

Criterion to be met by CDM projects	Specific challenges for CDM projects in land-use sector/rice production
Accurately measuring emissions and establishing a credible baseline	Very high due to high spatial and temporal variability
Assessing potential risks for continued emission savings due to unwanted changes	Very high due to the large number of participants (farmers) required for one project and lack of control of their crop management practices
Quantifying potential leakage of greenhouse gas emissions beyond project boundaries	High due to the nature of nonpoint emissions in land use and complex interactions at the landscape scale
Providing evidence on additionality of the mitigation option	Equivalent to other sectors
Ensuring sustainable development benefits	Equivalent to other sectors

Rice production also demonstrates the potential pitfalls of allocating CERs in the land-use sector. Water-saving techniques can reduce GHG emissions in a given area of rice land, but, in most cases, the saved water will then be used to irrigate more rice land or new crops in future seasons. Subsequently, emission savings are offset by emissions created in newly irrigated land. Ironically, if the saved water were channeled to other users, for example, in residential areas, one could rightfully claim CERs because of a net reduction in global warming potential (GWP, an aggregate measure for GHG emissions in terms of CO_2 equivalents).

Increasing food production is an absolute necessity for the human population and improved resource-use efficiencies are imperative to achieving this goal. As long as saved resources (water and fertilizers) are used to increase food production in a resource-efficient manner, it seems undue to account for new emissions as offsets or leakages of a mitigation project.

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Rice production and global climate change: scope for adaptation and mitigation activities

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Climate change has many facets, which include changes in long-term trends in temperature and rainfall regimes with increasing year-to-year variability and a greater prevalence of extreme events. The effects of these changing conditions on agriculture are obvious, but considerable gaps exist in our knowledge of how agricultural systems can be affected by both short- and long-term changes in climate and what implications these changes will have for rural livelihoods, particularly among the most vulnerable. For some regions and crops, opportunities for increased production exist, but, for most, there is simply not enough information available regarding impacts at scales that are relevant to decision making and research prioritization, and this has an adverse effect on the global net agricultural production (IPCC 2007).

Many of the climate change impacts on rice production discussed in this review are also applicable to other food crops. Higher temperature and aggravating climate extremes have negative effects on agricultural production and the socioeconomic conditions of farmers. In Indonesia alone, the total damaged area and production loss because of flooding were estimated to be 268,823 ha and 1,344 million t, respectively. With an average yield of 5.0 t ha^{-1}, economic loss was estimated to be about US\$353.7 million year^{-1}, affecting 4.4 million farm households or 22.4 million consumers. Compared with rice production, the specific impacts of these factors might be even worse for the production of crops that are more vulnerable to heat stress (e.g., wheat) and flooding (e.g., vegetables). On the other hand, the effects of sea-level rise on rice production will greatly exceed those on other crops, given the dominance of the rice crop in the delta regions. Likewise, rice production requires crop-specific considerations in terms of greenhouse gas (GHG) emissions because the carbon and nitrogen cycles of flooded rice fields are fundamentally different from those of other crops. Flooding is innate to irrigated, rainfed, and deepwater rice, resulting in emissions of methane.

Climate change presents an additional burden on the world's agricultural and natural resource systems, which are already coping with the growing food demand driven by population growth and higher income in developing countries. The challenge is compounded by the uncertainty and pace of climate change and its effects regionally. It is increasingly clear that climate change affects agricultural productivity. Changes in temperature and precipitation that accompany climate change will require farmers to adapt, but precisely where and how much is uncertain. At the same time, as a significant contributor of GHG and a potential sink for atmospheric carbon, agriculture can help mitigate climate change.

In this chapter, we look at the issues of rice agriculture in a world where climate change is increasingly a reality. Specific aspects of climate change have been broadly elaborated in comprehensive reviews devoted to rice production and crop production (Wassmann et al 2009a,b). The purpose of this new review is to provide an overview on (1) the expected impacts of climate change on rice production at different scales, (2) mitigation and adaptation options available to rice farmers, and (3) the economic implications of climate change and climate change policies at different scales.

Impact of and adaptation to climate-induced production constraints

The observed and projected effects of climate change are summarized in Table 1. These have been distilled from the recent 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007). A gradual increase in temperature, as reflected in fewer cold days and more frequent hot days, is already discernible in most regions and will intensify in the future. In turn, the higher background level of temperatures will further increase the intensity and frequency of heat spells. This trend, which is deemed almost certain for future conditions, has serious implications for agricultural production and human survival.

In the more immediate term, however, changes in precipitation may have a stronger impact on agricultural production than changes in temperature. Similarly, frequent floods because of heavy precipitation may result in higher yield losses under a progressing climate change. On the other hand, the predictions of extreme climate events under future climate conditions are considerably so uncertain that the 4th Assessment Report assigned a lower probability to this trend and to the other impacts (Table 1). Moreover, the increase in temperature will increase the sea level because of the thermal expansion of sea water and the rapid melting of glaciers and ice caps. As a consequence, fragile coastal and highly productive deltaic rice cultivation areas will be more exposed to inundation and salinity intrusion.

Table 1. Principal conclusions of the IPCC 4th Assessment Report (IPCC 2007).

Climate change impact and direction of trend	Probability of trend[a]	
	Recent decades	Future
Warmer days and nights and fewer cold days and nights over most land areas	Very likely	Virtually certain
More frequent hot days and nights over most land areas	Very likely	Virtually certain
Frequency of warm spells/heat waves increases over most land areas	Likely	Very likely
Frequency of heavy precipitation events increases over most land areas	Likely	Very likely
Areas affected by drought increase in many regions	Likely	Likely
Intense tropical cyclone activity increases in some regions	Likely	Likely

[a] Probability classes: likely, >66% probability of occurrence; very likely, >90% probability of occurrence; virtually certain, >99% probability of occurrence.

Higher temperatures

Higher temperatures affect rice yields through two fundamentally different processes: (1) gradual changes in metabolism and phenology and (2) spikelet sterility caused by temperatures (heat waves) beyond certain temperature/humidity thresholds. Rice is grown in many regions where current temperatures during grain filling are only slightly below the critical limits for spikelet sterility (Wassmann et al 2009b). The dry-season crop is potentially at risk in many regions in Asia, but, as of now, variety selection and flooding of fields (which reduces heat stress at the canopy level) usually keep the incidence of heat-induced sterility low. Nevertheless, it seems justifiable to assume that progressing climate change will soon cause heat-induced losses and thus necessitate varietal improvement in terms of heat tolerance.

Extremely high temperatures during vegetative growth reduce tiller number and plant height and negatively affect panicle and pollen development, thereby decreasing rice yield potential (Yoshida 1981). High temperature is of particular importance during flowering, which typically occurs at mid-morning. Exposure to high temperatures (i.e., >35 °C) can greatly reduce pollen viability and cause irreversible yield loss because of spikelet sterility (Matsui et al 2000). Studies conducted at the International Rice Research Institute (IRRI) in the early 1980s showed significant genotypic variation in high-temperature-induced spikelet sterility, and tolerant varieties were identified. Tolerance was shown to be associated with specific temporal and spatial characteristics of anthesis, number of pollen grains on stigma, and tolerance of pollen germination for high temperature. The low degree of stigma exsertion is probably associated with low spikelet sterility under high temperature. Current studies focus on the impact of heat stress on the degree and synchrony of anther dehiscence and stigma receptivity and on postpollination processes. This information can be used to develop screening tools to identify tolerant rice germplasm on a large scale and to develop marker-aided breeding and candidate gene isolation systems.

One breeding strategy to avoid high-temperature-induced spikelet sterility is to change the time of day when flowering commences to cooler periods earlier in the day to escape high temperatures. Wild rice and *Oryza glaberrima* accessions evaluated at IRRI varied by about 3 hours in time-of-day of flowering. The greater heat tolerance of popular cultivar IR64 compared with that of landrace Moroberekan may be due in part to its earlier and more synchronous flowering during the morning. A large mapping population derived from an IR64 × Moroberekan cross has yielded F_5 lines with earlier and more synchronous floret opening than IR64 or later and more synchronous flowering than Moroberekan. These lines have been crossed to develop populations suitable for genetic and molecular analysis of the control of floret opening time. Selecting for early-morning floret opening could initially protect rice fertility from future adverse effects of climate change until the genes and pathways involved become known. The development of rice that tolerates or avoids high temperatures during flowering is essential for future rice production but will immediately benefit farmers today since yield losses due to high temperatures are regularly reported.

The simulated yield reduction from a 1 ºC rise in mean daily temperature was about 5–7% for major crops, including rice (Brown and Rosenberg 1997, Matthews et al 1997). The yield reduction is mostly associated with the decrease in grain formation, shortening of growth duration, and increase in maintenance respiration. Peng et al (2004) reported that annual average nighttime temperature increased at a rate of 0.04 ºC y^{-1} from 1979 to 2003 at IRRI. The increase in nighttime temperature was three times greater than the increase in daytime temperature over the same period. More importantly, rice yield decreased by 10% for each 1-ºC increase in growing-season nighttime temperature in the dry season. Ziska and Manalo (1996) suggested that higher nighttime temperatures could also increase the susceptibility of rice to sterility with a subsequent reduction in seed set and grain yield, but the possible mechanism for this remains unknown.

The effects of increasing nighttime temperature on rice growth and yield are less understood than the effects of extremely high daytime temperatures on spikelet sterility during flowering. Biomass losses from increased maintenance respiration or differential effects of night vs day temperature on growth and crop phenology have been proposed as possible causes. Information is limited on genotypic variation of rice respiration in response to increased temperature. We particularly lack a clear understanding of the complex interactions between maintenance respiration and rice developmental stage, plant density and plant spacing, crop water and N status, temperature, and CO_2. Acclimation of maintenance respiration under long-term high-temperature treatment is also poorly understood in rice.

The average daily temperature during grain filling has a detrimental effect on at least three components of grain quality: enhanced chalkiness, lower amylose content, and modified cooking quality (higher gelatinization temperature). High temperature shortens the duration of grain filling because enzymes involved in starch synthesis are sensitive to high temperatures. High nighttime temperature also reduces the milled produce, that is, the yield of whole grains (head rice) after the milling process (Counce et al 2005).

With the sequence of the rice genome now available and with the cataloguing of gene function and allelic variability rapidly advancing, it is becoming simpler to relate phenotypic variation to functional allelic variability. To secure grain yield and quality in a warming world, it is necessary to embrace new tools and identify genetic strategies to overcome the effects of high temperature on sterility and grain filling and to develop selection tools that will enable rice breeders to continue to select high-yield and high-quality grain in a warmer world.

Aggravating climate extremes

Droughts

Drought regularly occurs on 23 million ha of rice land in Asia (Pandey et al 2007). Severe droughts in recent years, such as those seen in 2002-03 in India and in 2004 in Thailand, had a great impact on rice production and thus food security in these countries (Pandey et al 2007). Drought stress is highly damaging during the reproductive stage, specifically during flowering, but even drought in other stages or drought of milder intensity can also lead to big losses (Liu et al 2006). The current projections of climate change scenarios include a strong likelihood of a shift in precipitation patterns in many regions, exacerbating an almost universal trend for less water availability of the agricultural sector stemming from competition by other sectors (Bates et al 2008).

Aerobic varieties such as Apo have been developed for coping with drought stress, but these varieties showed a limited yield potential (3.4 t ha^{-1}) under ample water supply. A new generation of aerobic varieties achieves high yield potential under favorable conditions (4–5 t ha^{-1}) but retains the drought tolerance of aerobic varieties (Atlin et al 2008). Hybrid rice varieties represent another alternative as they showed a yield advantage of 1.2 t ha^{-1} under drought stress in the lowland areas of India (Atlin et al 2008). Ongoing research on the genetic basis of drought tolerance could be used to enhance drought tolerance in existing drought-susceptible mega-varieties, for example, capitalizing on a QTL on chromosome 12 explaining about 51% of the genetic variance for yield under severe upland drought stress (Bernier et al 2007), in several genetic backgrounds, including IR64.

Current rice production systems rely on ample water supply and thus are more vulnerable to drought stress than other cropping systems (O'Toole 2004). However, drought occurrence and its effects on rice productivity depend more on rainfall distribution than on total seasonal rainfall. Overall, it is now accepted that the complexity of the drought syndrome can be tackled only with a holistic approach, that is, by integrating plant breeding with physiological dissection of resistance traits and molecular genetics together with agronomic practices that can lead to better conservation and use of soil moisture and crop genotypes that adapt well to the environment. Some of the steps listed below that are involved in this multidisciplinary approach are also applicable to other climate-induced stresses:

- Define the target drought-prone environment(s) and identify the predominant type(s) of drought stress and the rice varieties preferred by farmers. Define the phenological and morphological traits that contribute substantially toward the adaptation to drought stress(es) in the target environment(s). A critical research aspect is the dissection of the interactions among drought, CO_2, and temperature.
- Use simulation modeling and systems analysis to evaluate crop response to major drought patterns under variable CO_2 and temperature scenarios and assess the value of candidate physiological traits in the target environment.
- Develop and refine appropriate screening methodologies for characterizing genetic stocks that could serve as donor parents for the traits of interest.
- Identify the genetic stocks for various putative, constitutive, and inducible traits in the germplasm and establish genetic correlations between the traits of interest and the degree of adaptation to the targeted drought stress.
- Use mapping populations and/or linkage disequilibrium mapping to identify genetic markers and QTLs for traits that are critical for stress resistance.
- Incorporate some of the components of relevant physiological traits into various genetic backgrounds to provide a range of materials with specific traits of interest (i.e., developing near-isogenic lines, recombinant inbred lines, and backcross populations) for improving adaptation to drought and abiotic stresses in locally adapted varieties.
- Harness functional genomics through transgenic technology and reverse genetics tools to understand the genetic control of relevant traits.

Floods

On the other end of the scale of stress symptoms, flooding can result in sustained submergence of the complete rice canopy, which eventually causes the death of the rice plants. Submergence is increasingly becoming a major production constraint, affecting about 10–15 million ha of rice fields in South and Southeast Asia and causing yield losses of up to US$1 billion every year (Dey and Upadhyaya 1996), a clear upward trend over recent years (Bates et al 2008). Conventional rice varieties can tolerate complete submergence only for a few days. A few tolerant rice varieties, however, were already identified in the 1970s (Vergara and Mazaredo 1975) and have been used as donors of tolerance by breeders. The gene responsible for conferring submergence tolerance has been identified and recently been fine-mapped (Xu and Mackill 1996, Toojinda et al 2003, Xu et al 2006). The information on the genes located in the *SUB1* locus now facilitates in-depth analyses of the molecular and physiological tolerance mechanisms and, more importantly, triggers a breakthrough in marker-assisted breeding of submergence-tolerant rice varieties (for a time-lapse series video, visit www.irri.org/timelapse.asp).

A novel marker-assisted backcrossing (MAB) approach was developed that could facilitate the introgression of *SUB1* into the background of widely grown rice varieties or the so-called mega-varieties. With this new technique, submergence-tolerant plants can be developed by two to three backcrosses (BC_2F_3 or BC_3F_2) into the recipient mega-variety (Septiningsih et al 2009). However, crossing IR64-Sub1 with the original IR64 showed less tolerance in the F_1 (first generation) progenies compared with IR64-Sub1, indicating that the tolerance alleles of *SUB1* should be present in both hybrid parents to maintain a high level of tolerance. The main advantage of using mega-varieties as recipient parents is that farmers' and consumers' preferred traits present in these varieties are preserved and the risk of introducing undesirable traits is considerably reduced.

Sub1 versions of six mega-varieties (IR64, Swarna, BR11, TDK1, Samba Mahsuri, and CR1009) were developed at IRRI and tested by national institutes in eight Asian countries. Promising submergence-tolerant rice varieties have been officially released in Indonesia, India, the Philippines, and Bangladesh. Recently, massive upscaling and dissemination of Sub1 varieties began in Indonesia and the Philippines. Sub1 varieties along with their tolerance for flood conditions were found to be susceptible to diseases such as neck blast, sheath blight, and false smut in the Philippines. Hence, precautionary measures such as identification of regions where these diseases are endemic have to be considered while scaling up the Sub1 varieties. Alternatively, the *SUB1* gene could be introgressed into a high-yielding blast- and BLB-resistant variety through MAB. Detailed information related to the vulnerable flood-prone areas, potential varietal selection through farmer participatory field trials, recent progress of Sub1 varietal adoption in different counties, etc., can be obtained from IRRI's official Web site (www.irri.org/flood-proof-rice/).

In the context of climate change, submergence tolerance could be deemed crucial in coping with cyclone effects and the rise in sea level. Large sections of Asian coastlines are fringed with rice production systems that usually receive heavy rainfall during the wet season. This may coincide with strong sea disturbances, inundating the coasts because of high tides. Because of the combination of high rainfall and high tides, the rice crop in coastal areas experiences submergence with moderately saline water, specifically during early crop growth. With the projected sea-water rise, such saltwater intrusion in coastal areas would be more frequent in the future. Therefore, both submergence and salinity stress tolerance are crucial to the survival of rice plants in the initial 5–6 wk.

Salinity

Salinity problems are aggravated by high temperatures, and thus climate change, because transpirational demand leads to a higher accumulation of salt. This interaction of salt and heat stress is especially relevant in the arid/subarid regions with high transpirational losses in plants. Moreover, salinity problems will become more rampant in coastal and deltaic regions affected by the rise in sea level. Salinity tolerance is important at both seedling and reproductive stages of the rice plant. Some existing landraces of rice can withstand very high salinity and could be good candidates for breeding, but inherently they yield poorly. Salinity-tolerant genotypes are available in improved backgrounds, but, considering future climate projections, they still have to be enhanced.

IRRI's efforts in generating salt-tolerant rice resulted in the identification of *Saltol*, a major QTL on chromosome 1 (Gregorio 1997, Bonilla et al 2002). This QTL was introgressed using MAB to incorporate seedling-stage salt tolerance in BR28, an adapted variety for the boro season in Bangladesh. Salt tolerance at the seedling stage is essential during the monsoon season, mainly during transplanting of seedlings and in the following couple of weeks until the monsoon rains wash the salts from the soil. Advanced yield trials including putative salt-tolerant entries in Bangladesh showed better performance under low salinity (4–6 dS m^{-1}), whereas they had low yield in highly saline (17 dS m^{-1}) screening sites; this indicates the need to intensify the search for entries with high tolerance for salinity at both vegetative and reproductive stages. A potential but largely unexploited source of such variation is the Genetic Resources Center at IRRI, which houses more than 110,000 rice accessions. Moreover, in coastal rice-producing regions, submergence of the rice crop in saline water is much more detrimental than in nonsaline water because of the combination of stresses (Thein 2007). There is progress at IRRI in using *Saltol* and the submergence tolerance *SUB1* gene toward the development of rice varieties with both submergence and salinity tolerance at the seedling stage.

Vast regions of the Indo-Gangetic Plains have been abandoned because of their high sodic level (pH 10.2) and low organic matter content. With continued protests against the mining of gypsum previously used to reclaim these lands, developing highly salt-tolerant rice varieties is the only hope for farmers in these regions. Recently, under the Stress-Tolerant Rice for Poor Farmers in Africa and South Asia (STRASA) program, four salt-tolerant varieties were tested. CSR36 gave an average yield of 2.1 t ha^{-1} at a pH of 9.8–10, while local check Moti produced a negligible yield. Earlier, CSR23 was found to be superior during the 4-year field trials; it was officially released in 2004 for the alkaline soils of Uttar Pradesh and Haryana and the coastal saline soils of West Bengal, Tamil Nadu, Kerala, Maharashtra, and Gujarat. This variety could withstand sodicity stress of up to 8 dS m^{-1} (pH 2–10). Apart from its ability to withstand high sodicity, it was found to be moderately resistant to blast, neck blast, and brown spot. Hence, CSR23 and CSR36 are potential materials to be targeted for sustaining rice yields in fragile coastal regions.

Very recently, Alpuerto et al (2009) used economic impact analysis to compare the benefits of using molecular techniques (molecular MAB) and conventional breeding and documented that 3¬6 fewer years could be used to develop salt-tolerant varieties by adopting the MAB technology. This approach resulted in an incremental benefit of US$49.1 to $498.9 million, depending on the country. Hence, adopting advanced molecular technology could further help reduce the duration required for developing climate-proof (heat-, submergence-, salinity-, and drought-tolerant) rice varieties, leading to higher economic benefit and reduced poverty among thousands of small and marginal rice farmers around the world.

Impacts and adaptation in a regional context

Sea-level rise in delta regions

South, East, and Southeast Asia comprise several mega-deltas, of which nine are larger than 1 million ha (IPCC 2007). Rice production in these mega-deltas forms the backbone of the agricultural sector in many Asian countries and is responsible for a large share of rice that is marketed internationally. At the same time, the topographic settings and vicinity to the coastline render deltaic regions especially vulnerable to the consequences of climate change, namely, those of sea-level rise and storm surges. Observations from tide gauges indicate that the mean global sea level has risen by about 10–25 cm over the last 100 years (IPCC 2007). Based on temperature change projections, model projections of future global mean sea-level change show a rise between 13 and 94 cm by 2100, with a central estimate of 49 cm (IPCC 2001).

No crop other than rice can be grown under these adverse conditions of unstable water levels and, in many locations, salinity. In Vietnam, the Mekong Delta alone yields 54% of the national rice production with the Red River Delta adding another 17% (data for 2005 from IRRI 2008). Production growth in the Mekong Delta has driven the steadily increasing rice production in Vietnam over the last decades. The Mekong Delta contributes to the vast share of rice exports in Vietnam, which accounts for 4.7 million t of rice every year, making it the second largest exporter worldwide (IRRI 2008). Thus, any shortfall in rice production in this area because of climate change would not only affect the economy and food security in Vietnam but also have repercussions on the international rice market. The deltas of Myanmar (Irrawaddy) and Bangladesh (Ganges-Brahmaputra) provide 68% and 34% of the national rice production, respectively. The rice produced in these deltas is almost entirely used for domestic consumption since Myanmar exports only a relatively small amount of rice (100,000 t year^{-1}) and Bangladesh is a rice-importing country.

However, a rising sea level may deteriorate rice production in a sizable portion of the highly productive rice land in the deltas (Wassmann et al 2004). In the Asian mega-deltas, rice is the dominant crop and, in most cases, the only crop that can be grown during the monsoon season. Higher sea levels impede gravitational river discharge and accelerate tides further inland and create, in combination with heavy rainfall, serious waterlogging and prolonged stagnant floods. Only a few low-yielding landraces in these areas have evolved to withstand such conditions. However, prospects to enhance adaptation to these conditions using molecular tools are evident. While flashfloods during the vegetative stage can now be addressed by introgression of the *SUB1A* gene, additional genes are needed to increase tolerance for stagnant flooding, that is, prolonged partial flooding with 30–60-cm water depths, causing high mortality, suppressed tillering ability, reduced panicle size, and high sterility.

Seasonal climate forecasting in ENSO-affected regions

Scientific advances in meteorology and informatics have made it possible now to forecast drought within a seasonal time frame. Various indicators such as the El Niño southern oscillation (ENSO) index could potentially enhance drought preparedness at the national level and assist farmers in making more efficient decisions regarding the choice of crops and cropping practices.

In unfavorable rainfed environments, precipitation variability is by far the most important factor for variability in crop production and agricultural economic risk. Detailed agricultural management strategies have been developed for coping with rainfall variability. These strategies are widely found in international dryland agriculture: 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 regarding improved information systems. Recent developments in the application of seasonal climate forecasts in the agriculture sector suggest that there is a large potential for enhancing agricultural risk management, enabling farmers to tailor management decisions to the cropping season (Meinke and Stone 2005, Hansen et al 2007). The season- and region-specific prospects of agricultural production can be quantified using spatially and explicitly applied simulation models that 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 thus allow retrospective investigation of the potential value of seasonal climate forecasts for a particular problem (Meinke and Stone 2005). The integration of both seasonal and interannual climate forecasting and crop modeling is an integrated agricultural tool that gives information for increasing readiness to climate variability and change in agricultural planning and operation. The seasonal climate forecast has high economic value if management strategies can be applied in adequate complexity and amount.

Boer et al (2009) analyzed the applicability of seasonal climate forecast indices such as ENSO for rice and maize crop forecasting in Indonesia. Generally speaking, a negative correlation between rice production and sea-surface temperature means that the higher the sea-surface temperature, the lower the rice production; for maize, the correlation is positive. This is probably because the occurrence of El Niño may not significantly affect the wet-season planting area in Indonesia and because the water requirement for maize is much lower than that for rice. In addition, the occurrence of El Niño may increase the amount of radiation received during the wet season. Further analysis also suggests that the occurrence of the ENSO during the dry season will affect crop production in that season and region. It is clear that the intensity and frequency of the El Niño phenomenon increase as global temperature increases. This means that climate change will have an impact on the occurrence and strength of both droughts and floods. Also, the onset of the monsoon and the length of the dry and wet seasons will be influenced. These changes will have a strong impact on rice production; thus, strong seasonal climate forecasting systems are needed for major rice production areas in Asia.

Jones et al (2000) estimated monetary returns on decisions based on reliable estimations of the phases of the El Niño indices and terciles of growing-season rainfall in the USA. They showed that crop rotation systems of rainfed crops differed among ENSO events and that the modification of maize management (planting date, plant density, and N fertilizer) based on rainfall terciles (seasonal climate forecasts) returned higher profit than optimization based on phases of the ENSO. 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 cropping systems that farmers manage (Hansen et al 2007, Meinke et al 2006). In practice, however, such specific and detailed information is rarely available to farmers, especially in rice-producing developing countries of Asia.

However, operational seasonal climate forecasts are typically given over large areas. The format of such forecasts is commonly a two- (below/above median rainfall) or three (rainfall terciles)-category format and the forecast is given as, for example, "chance of receiving above median rainfall." The International Research Institute for Climate and Society (http://iri.columbia.edu, Goddard et al 2003) issues forecasts in a three-category format on a global scale. However, inappropriate content is one of the obstacles to adoption of seasonal climate forecasts by potential users (Nicholls 2000). This is particularly true in rice-producing countries in Southeast Asia such as the Philippines. If farmers of the Philippines gain access to more timely and reliable seasonal rainfall forecasts, the risks in crop production can be significantly reduced by better matching the choice of crop and planting time to anticipated rainfall. This, in turn, increases 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 higher income or degree of food security. At the same time, they can reduce costs associated with replanting and having to fall back to shorter duration crops with lower yield potential.

GHG emissions

Rice production plays a significant role in the global source strength of greenhouse gases (GHGs). Anaerobic decomposition in rice fields results in the release of substantial amounts of methane into the atmosphere. While methane is the most important component of the global warming potential (GWP) of rice production, the interactive nature of carbon and nitrogen cycles in rice fields demands a consideration of the other GHGs, namely, N_2O and CO_2, in view of full GWP accounting.

Strength of GHG source in rice production

Methane. The magnitude and pattern of methane emissions from rice fields are mainly determined by water regime and organic inputs and, to a lesser extent, by soil type, weather, tillage management, residues and fertilizers, and rice cultivar. Flooding is a prerequisite for sustained emissions of methane. Mid-season drainage, a common irrigation practice adopted in major rice-growing regions of China and Japan, greatly reduces methane emissions. Similarly, rice environments with an inadequate supply of water, such as rainfed rice, have a lower emission potential than irrigated rice. Organic inputs stimulate methane emissions as long as fields remain flooded. In addition to management factors, methane emissions are also affected by soil parameters and climate.

In spite of considerable efforts to quantify methane emissions from rice fields, the estimates of this source strength are still attached to major uncertainties. Intensive field measurement campaigns have clearly revealed the complex interaction of water regime as the major determinant of emissions on the one hand and several other influencing factors on the other. Given the diversity of rice production systems, reliable upscaling of methane source strengths requires a high degree of differentiation in terms of management practices and natural factors. Modeling approaches have been developed to simulate methane emissions as a function of a large number of input parameters, namely, modalities of management as soil and climate parameters.

A methane rice map (obtained from the EDGAR database) reflects distinct "hot spots" in China and India as well as in Southeast Asia. These hot spots in China, northwest India, Vietnam, and the Philippines correspond to areas with high abundance of rice fields and dominance of irrigated rice. Eastern India, northeast Thailand, and southern Myanmar have a relatively high amount of rainfed rice (with a lower methane emission potential than irrigated rice), but the prevalence of rice as compared with other forms of land use mark these regions with high methane emission potential. Yan et al (2009) recently estimated the methane emissions from global rice fields based on the Tier 1 method described in the 2006 IPCC guidelines (IPCC 2007) with country-specific statistical data regarding rice harvest areas and expert estimates of relevant agricultural activities. The estimated global emissions for 2000 were 25.4 Tg year^{-1}, which is at the lower end of earlier estimates and close to the total emissions summarized by individual national communications. These results are in line with other assessments of methane source strengths from rice fields. According to the latest summary by the IPCC (Denman et al 2007), rice fields emit 31–112 Tg of CH_4 per year, about 12–26% of the anthropogenic methane sources, or about 9–19% of the global methane emissions (base year: 1983-2001).

Nitrous oxide. According to the latest IPCC summary (Denman et al 2007), arable lands emit about 2.8 Tg N of N_2O per year, about 42% of the anthropogenic N_2O sources, or about 16% of the global N_2O emissions, but rice fields have not been distinguished from upland fields. Early studies found N_2O emissions from rice fields to be negligible (Smith et al 1982). However, later studies suggest that rice cultivation is an important anthropogenic source not only of atmospheric methane but also of N_2O (Cai et al 1997).

The initial IPCC guidelines use a default fertilizer-induced emission factor (EF) of 1.25% of net N input (based on the unvolatilized portion of applied N) and a background emission rate for direct emissions from agricultural soil of 1 kg N ha^{-1} year^{-1} (IPCC 1997). Later, IPCC revised the EF to 1% for N additions from mineral fertilizers, organic amendments, crop residues, and N mineralized from mineral soil as a result of the loss of carbon in the soil (IPCC 2007). These revised guidelines provide two standard conversion factors for determining N_2O emissions based on fertilizer application—for flooded rice, 0.003 of the fertilizer nitrogen becomes N_2O, whereas, for all other crops, the ratio is 0.01. However, there is no distinction as to crop and water management effects on N_2O emissions in the IPCC accounting procedure.

Carbon dioxide. Rice soils that are flooded for long periods in the year tend to accumulate soil organic matter (SOC), even with complete removal of the aboveground plant biomass (Bronson et al 1997). Significant inputs of C and N are derived from the biological activity in the soil-floodwater system (Roger 1996), and conditions are generally more favorable for the formation of conserved SOC (Olk et al 1998, Kirk and Olk 2000). In China, it is estimated that the current C sequestration rate in irrigated rice cultivation is 12 Tg C year^{-1} and that these systems have induced a total enrichment of SOC storage of about 0.3 Tg C (Pan et al 2003).

Mitigating options

Technological approaches. Many mitigation options for GHG emissions through field management have been suggested, which can be classified into four categories: changes in water management, organic matter applications, soil amendments, and others (Yagi 2002). Changing water management appears to be the most promising option and is particularly suited to reducing emissions in irrigated rice production, such as in the rice ecosystem with the highest emission potential.

Securing a stable and adequate supply of water as in the past will become more difficult even for the irrigated rice ecosystems because of the effects of climate change and competition between industrial and domestic usage. Linked with this water resource issue, the mitigation options of the GWP of rice fields through water management are worthy of attention.

Mid-season drainage or intermittent irrigation, which prevents the development of soil reductive conditions, is considered to be an effective option for mitigating methane emissions from rice fields (Yagi et al 1997). A statistical analysis of a large dataset from Asian rice fields indicated that, compared with continuous flooding, a single mid-season aeration can reduce average seasonal methane emissions by 40%, and multiple aeration reduces them by 48% (Yan et al 2005). Li et al (2006) estimated that, despite the large-scale adoption of mid-season drainage, a large potential still exists for additional methane reductions of 20–60% from Chinese rice fields over 2000-20 with the process-oriented denitrification and decomposition (DNDC) model. Through the analysis, water management strategies appeared to be the most technically promising GHG mitigation alternative, with shallow flooding providing the additional benefits of both water conservation and increased yields.

However, mid-season drainage or reduction in water use increases N_2O emissions by creating nearly saturated soil conditions, which promote N_2O production (Zheng et al 2000). There are reports that mid-season drainage increased and decreased the net GWP of rice fields. Cai et al (1999) reported that the GWP of N_2O emissions was even higher than that of methane emissions from Chinese rice fields with mid-season drainage when large amounts of chemical fertilizer (364.5 kg N ha^{-1}) and farmyard manure (5 t ha^{-1}) were applied. Bronson et al (1997) found that the total GWP of continuously flooded fields was lower than that of fields drained in mid-season when no straw was applied, but it was higher when straw was applied. There seems to be a broadening consensus that mid-season drainage decreases the net GWP of rice fields judging from the datasets that have been accumulated in the past. According to an empirical model proposed by Yan et al (2005), mid-season drainage generally tends to be an effective option for mitigating net GWP, though 15–20% of the benefit gained by decreasing methane emissions was offset by the increase in N_2O emissions. Further, Li et al (2004) reported that mid-season drainage reduces net GWP compared with continuous flooding; 65% of the benefit gained by decreasing methane emissions from rice fields in China was offset by an increase in N_2O emissions, as determined by the DNDC model. However, based on the 2006 IPCC guidelines, Yan et al (2009) estimated that the increased global warming potential resulting from the increase in N_2O emissions was offsetting only approximately 2.7% of the reductions achieved through lower methane emissions.

We can conclude that mid-season drainage has potential to effectively mitigate the net GWP from rice fields, especially when larger amounts of rice straw are returned into the soil. However, there is a risk that N_2O emissions offset a reduction in methane emissions when N fertilizer is applied at a high rate. Thus, this modification of water management should preferably be coupled with efficient fertilizer application as a means to reduce GHG emissions in addition to savings in irrigation water and fertilizers.

The drainage timing and span of conventional water management depend on farmers' empirical knowledge and customary practices. To provide farmers with specific criteria for draining and watering from the viewpoint of water saving, the International Rice Research Institute (IRRI) has been developing and disseminating an alternate wetting and drying (AWD) irrigation management technique that provides farmers with specific criteria of soil water for judging the timing of watering to avoid imposing drought stress on rice plants (Bouman et al 2007). This AWD technique does not force drainage to save water but reduces field water application from 15% to 20% without significantly affecting yield, thus increasing the productivity of total water input (Tabbal et al 2002, Belder et al 2004). At this point, IRRI is challenged to develop a new AWD system that produces high yield, water savings, and low GWP compatibility.

International agreements on adaptation in the agriculture sector

While the situation for mitigation in the context of international agreements is discussed elsewhere in this volume (Wassmann, this volume), this chapter will focus on adaptation. Since rice production is predominantly conducted in developing countries, the situation for funding its adaptation to climate change is tightly linked to the "Adaptation Fund" that was launched at the 13th Conference of Parties (COP13) held in Bali in 2007. Within the Bali road map, all parties opted for enhanced cooperation to "support urgent implementation" of measures to protect poorer countries from climate change. In particular, the least developed countries (LDCs) should be supported by funding their National Adaptation Programs of Action (NAPAs). Most LDCs, including major rice producers such as Bangladesh, Cambodia, and Laos, have now submitted their NAPAs to the United Nations Framework Convention on Climate Change (UNFCCC) (Myanmar and Nepal have not done it yet despite their classification as LDCs).

The principles of the Adaptation Fund have been reiterated in the Copenhagen Accord at COP15 (2009), namely, that "developed countries shall provide adequate, predictable, and sustainable financial resources, technology, and capacity building to support the implementation of adaptation action in developing countries." In combination with funds allocated for mitigation, the collective commitment by developed countries accounted for US$30 billion for 2010-12. In line with the Bali road map, the Copenhagen Accord confirmed that "funding for adaptation will be prioritized for the most vulnerable developing countries that include the LDCs."

However, the Copenhagen Accord failed to deliver clear modalities and time lines for generating and distributing these envisaged funds. In fact, the Copenhagen Accord was not adopted by the COP but was just taken note of. This status has later been corroborated through communications to the secretariat in which several countries have expressed their clear understanding that the Copenhagen Accord is a political document and not legally binding. However, the Accord could have value to facilitate the ongoing negotiations within the areas of convergence reflected in the text; the need for adaptations appears to be one of the least contentious issues in the current state of the debate.

Outlook: current advances and future prospects

Technological progress alone will be insufficient to cope with climate change, but research on germplasm improvement and crop management represents a pivotal component in the climate policy. More than 800 million people in tropical and subtropical countries are currently food-insecure. Their situation is expected to worsen, and the number of food-insecure people is likely to increase as a consequence of climate change impacts, unless drastic measures are implemented to increase their capacity to adapt to climate change.

The rice-cropping system is the economic backbone of many Asian nations and even a small decrease in productivity will drastically imperil food security. Therefore, the system needs to be modified and diversified to increase adaptability to the changing climate. While developing more tolerant crop varieties is at the heart of adaptation measures, the efficiency of this approach can significantly be increased by geographic analysis of vulnerable regions and regional climate modeling to identify temperatures or CO_2 levels above which major yield losses are experienced, and thus site-specific adjustments in crop management can be made to optimize the production system. Several uncertainties that limit the accuracy of current projections on temperature increase and changes in precipitation pattern and their geographic distribution need to be resolved. There are several ways by which the adverse impact of climate change can be mitigated, so that agriculture can cope with the changing climate. There is a need to develop a policy framework for implementing the adaptation options so that farmers are saved from the adverse impacts of climate change.

The scientific progress made in understanding the physiology of abiotic stresses and the development of biotechnology tools have opened up promising opportunities for making a significant impact through improved technology. However, as the 2008 rice crisis demonstrated, agricultural research in general remains grossly underinvested in developing countries in Asia. This is a cause for concern, not only for climate change adaptation and mitigation but also for promoting overall agricultural development.

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Notes

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