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# Climate Change Adaptation through Rice Production in Regions with High Poverty Levels

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## Abstract

Climate change will severely set back agricultural development in tropical countries, where an increasing share of the poorest and most vulnerable population resides. Widespread and persistent poverty is a longstanding problem in both South Asia and Africa, particularly in areas without irrigation, areas referred to as "rainfed ecosystems". With the inherent problems in the agricultural sector -- such as lack of finances, poor irrigation infrastructure, etc. — production levels in South Asia and Sub-Saharan Africa will be more affected by climate variability and change than in most other parts of the world. This review describes the expected impacts of climate change on rice (*Oryza sativa L.*) production with emphasis on these two subcontinents and also outlines possible response strategies in rice production. Given recent progress in developing more resilient rice production systems, climate adaptation in this important income and food source could prove to be a key factor to forestall – or at least mitigate the adverse effects of climate change in South Asia as well as Sub-Saharan Africa.

## 1. Introduction

The conclusions of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) published in early 2007 leave no doubt that the Earth's climate is changing in a manner unprecedented in the past 400,000 years. The report corroborated previous scenarios that by 2100 mean planet-wide surface temperatures will rise by 1.4 to 5.8 °C, precipitation will decrease in the sub-tropics, and extreme events will become more frequent (IPCC, 2007). However, changes in climate are already being observed—the last 60 years were the warmest in the last 1000 years and changes in precipitation patterns have brought greater incidence of floods or drought globally. These changes are driven by increasing concentrations of greenhouse gases, namely $CO_2$, $CH_4$ and $N_2O$, and will also affect agro-climatic conditions for food production systems. The potentially beneficial effects of increases in $CO_2$ may be offset by concomitant temperature stress and other factors such as the increases in ground level (tropospheric) ozone concentrations. Most developing countries are not well prepared to deal with the negative impacts to be expected as a result of climate change and are therefore most vulnerable to its consequences.

## 2. Role of rice in regions with high poverty level

Poverty is widespread in both South Asia and Sub-Saharan Africa (SSA) and there is also an interesting correspondence of poverty and the composition of rice environments in the respective countries (Fig. 1). Broadly speaking, high poverty levels coincide with the prevalence of rainfed rice systems – or vice-versa. Rainfed crops are likely to be worse hit by climate change because of the limited mechanisms for coping with variability of precipitation. Thus, adaptation in rainfed rice production can be seen as a promising entry point to buffer the consequences of climate change amongst the poorest of the poor.

In Asia, rice is the staple food (up to 60% of energy intake), not only in the rural areas, but also for the urban poor. Rice production is of overwhelming economic significance in Asia and is the principal source of employment and income in rural areas. The availability of cheap rice is also an important factor to meet the nutritional needs of the underprivileged urban population.

Rainfed ecosystems comprise a total of 60 million hectares in Asia, whereas this figure is only 6.8 million ha for SSA. However, rice is at present the fastest growing food source in SSA. Rice yields in SSA are generally below 2.5 t/ha resulting in insufficient production to meet demands. The deficit is made up by rice imports which rose from 1 million metric tons in 1972 to more than 7.5 million tons in 2004 in Africa (IRRI 2007). Rainfed rice production has an enormous potential to increase food security in the humid/subhumid zone of SSA under present climatic conditions, but it is unclear how this potential will evolve under climate change.

## 3. Impacts of Climate Change on Rice Production

Increasing $CO_2$ concentration in the atmosphere has a positive effect on crop biomass production, but its net effect on rice yield depends on possible yield reductions associated with increasing temperature. For every 75 ppm increase in $CO_2$ concentration rice yields will increase by 0.5 t $ha^{-1}$, but yield will decrease by 0.6 t $ha^{-1}$ for every 1 °C increase in temperature (Sheehy et al., 2005). In a separate study, the simulated yield reduction from a 1ºC rise in mean daily temperature varied from 5-7% for major crops, including rice (Matthews et al., 1997). The yield reduction was mostly associated with decrease in sink formation, shortening of growth duration and increase in maintenance respiration (Matthews and Wassmann, 2003).

Enclosure studies with $CO_2$ enrichment have generally shown significant increases in rice biomass (25-40%) and yields (15-39%) at ambient temperature, but those increases tended to be offset when temperature was increased along with rising $CO_2$ (Ziska et al., 1996a,b; Moya et al., 1998). Yield losses caused by concurrent increases in $CO_2$ and temperature are primarily caused by high-temperature-induced spikelet sterility (Matsui et al., 1997a), but there is a lack of more detailed studies on $CO_2$ × temperature response curves. Increased $CO_2$ levels may also cause a direct inhibition of maintenance respiration at night temperatures higher than 21°C (Baker et al., 2000). Rice response to elevated $CO_2$ also depends on nitrogen supply. If additional $CO_2$ is given when N is limited, lack of sinks for excess carbon (e.g. tillers) may limit the photosynthetic and growth response (Ziska et al., 1996b). There is evidence for genotypic variation in response to increasing $CO_2$ and temperature (Ziska and Teramura, 1992; Ziska et al., 1996a; Moya et al., 1998), but as of now genes, traits or mechanisms associated with this have not yet been identified.

The magnitude of the $CO_2$ fertilization effect remains under debate. More recent measurements using large, free-air $CO_2$ enrichment (FACE) systems have generally found that stimulation of crop yield was smaller than reported from enclosure studies and that acclimation of photosynthesis occurs because crops attempt to maintain balance in N and other resources (Ainsworth and Long, 2005). In a large-scale FACE system dedicated to investigation of rice, located in northern Japan, yield increases due to elevated $CO_2$ (+200 ppm) averaged 7 to 15% over three years (Kim et al., 2003). There is a lack of FACE studies for measuring $CO_2$ response curves across a wider range of elevated $CO_2$ concentrations under field conditions, which is required for more accurate scaling of physiological results and validation of crop models (Ainsworth and Long, 2005).

Climate change includes gradually increasing average temperature as well as increased frequency and magnitude of extreme weather events (Mirza, 2003). In rice, extreme maximum temperature is of particular importance during flowering which usually lasts two to three weeks. Exposure to high temperature for a few hours can greatly reduce pollen viability and, therefore, cause yield loss. Spikelet sterility is greatly increased at temperatures higher than 35 °C (Osada et al., 1973; Matsui et al., 1997b) and enhanced $CO_2$ levels may further aggravate this problem, possibly because of reduced transpirational cooling (Matsui et al., 1997a). It is also likely that high temperature stress on spikelet fertility depends on humidity because field observations in some high-yielding rice areas with a drier climate and high temperature (e.g., New South Wales and Southern Iran) suggest no significant increase in spikelet sterility even at temperatures >40°C (P. Snell, F. Moradi, pers. commun.). A key mechanism of high temperature-induced floret sterility in rice is the decreased ability of the pollen grains to swell, resulting in poor thecae dehiscence (Matsui et al., 2000). Significant genotypic variation in high-temperature induced floret sterility exists. Among nine Japonica cultivars, the temperature that caused 50% sterility varied by 3°C between the most tolerant and susceptible cultivars (Matsui et al., 2001). The length of basal dehiscence has been proposed as a morphological trait for high temperature tolerance that could be used in breeding programs (Matsui et al., 2005). Another strategy is to change the time-of-day when flowering commences to cooler periods. Wild rice accessions evaluated at IRRI varied by about 3 hours in time of flowering (Howell, pers. comm.). Shifting flowering to the early morning hours could protect rice fertility from future adverse effects of climate change, but the genes involved need to be identified.

Effects of increasing minimum temperature on rice growth and yield are less understood than the effects of extremely high day temperatures on spikelet sterility. There is evidence that increasing night temperature is the main cause of increases in global mean temperatures since the middle of the 20th century (Kukla and Karl, 1993). At IRRI, minimum temperatures in the wet and dry seasons have increased at a rate of 0.04°C $yr^{-1}$ from 1979 to 2003 (or 1°C in 25 years), but there was only a small increase in the wet season and no increase in the dry season maximum temperature (Sheehy et al., 2005). During this period, rice yields in IRRI's long-term trials have also shown a negative correlation with increasing night temperature (Peng et al., 2004). Reasons for this negative correlation and apparent yield decline are not well understood. Variation in solar radiation, increased maintenance respiration losses or differential effects of night vs. day temperature on tillering, leaf-area expansion, stem elongation, grain filling, and crop phenology have been proposed as possible causes (Peng et al., 2004; Sheehy et al., 2005). In a recent climate chamber study, there was first evidence of possible genotypic variation in resistance to high night temperatures

(Counce et al., 2005). Overall, these processes are not well understood and they are also not captured well in crop models that seek to predict rice response to climate and climatic change.

There is little information concerning the respiratory behavior of the rice crop throughout its growth cycle. Carbon losses due to growth and maintenance respiration typically amount to 40 to 60% of the total carbon fixed by a crop (Pritchard and Amthor, 2005). In tropical areas, this percentage may even be higher. Early in the growing season, growth respiration dominates. At later stages, maintenance respiration may account for 50% of the total respiration loss and it is much affected by environmental conditions within the crop canopy. Since growth respiration is proportional to crop biomass, it can only be reduced by lowering the growth rate or by changing the biochemical composition of the phytomass produced. In contrast, maintenance respiration can be altered through genetic improvement and management. Some evidence of genetic variation in maintenance respiration exists for other crops (Winzeler et al., 1988; Earl and Tollenaar, 1998) and there have also been attempts to select for more respiration-efficient germplasm (Wilson and Jones, 1982). Little is known for rice under field conditions. We particularly lack a clear understanding of the complex interactions between maintenance respiration and developmental stage, plant density/plant spacing, crop water and N status, temperature, and $CO_2$. Short-term (seconds to hours) temperature increases stimulate crop respiration rates, but there is little information about long-term (days to years) temperature acclimation of maintenance respiration in crops (Pritchard and Amthor, 2005). If warming enhances growth and crop biomass, it is also likely to enhance both growth and maintenance respiration. The net effect on yield depends on when in the growth cycle the warming occurs. Experimental evidence on the net effect of increasing $CO_2$ on respiration losses is contradictory.

High $CO_2$ levels and/or temperature are likely to affect crop development rates. In most cases, elevated $CO_2$ or temperature seem to hasten development, but it has also been shown in soybean, for example, that increased $CO_2$ can actually prolong crop duration (Morgan et al., 2005). These interactions are not well understood and most crop models for rice are not well-equipped to handle the effects of $CO_2$ on phenological development.

Climate change is likely to have an impact on water use and water use efficiency in rice. Temperature increases are likely to cause increased evapotranspiration losses. However, there is new evidence that $CO_2$ enrichment can increase water use efficiency due to a combination of reduced transpiration and increased biomass production resulting from reduced stomatal conductance and increased shading from larger leaves (Yoshimoto et al., 2005).

Mineral stress remains a mostly unknown link in understanding how global climate change will affect plants, requiring better integration of quantitative genetics with mechanistic models of plant response to mineral nutrient supply (Lynch and St. Clair, 2004). It is likely that warming will accelerate many microbial processes in the soil-floodwater system, with consequences for the C and N cycle. Crop residue decomposition patterns may change. Increased soil temperature may also lead to an increase in autotrophic $CO_2$ losses from the soil caused by root respiration, root exudates, and fine-root turnover. Rice plants growing under higher soil temperature (e.g., in a water-saving irrigation regime) may change their C and N partitioning as compared to those growing in a cooler environment (e.g., continuous flooding). In the rice FACE system in Japan, a strong positive interaction between N supply and carbon gain under $CO_2$ enrichment has been observed (Kim et al., 2003). This interaction was caused by an increase in leaf area index (LAI) with increasing N availability, which enhanced the positive effect of higher quantum yield under $CO_2$ elevation.

$CO_2$ enrichment and changes in temperature may also affect weed ecology, the evolution of weed species over time and the competitiveness of $C_3$ vs $C_4$ weed species (Ziska, 2000; Ziska, 2003a; Ziska, 2003b). Generally, we know little about potential changes in population dynamics of weeds, insects, and diseases in response to climate change and what implications this may have for biodiversity and Integrated Pest Management concepts in a world of changing climate. Similar changes will also occur when irrigated rice systems undergo significant changes in cropping systems or crop management practices that lead to more frequent or longer aerobic periods.

The simulated yield reduction from a 1°C rise in mean daily temperature was about 5-7% for major crops, including rice (Matthews et al., 1997). The yield reduction is mostly associated with decrease in sink formation, shortening of growth duration and increase in maintenance respiration (Matthews and Wassmann, 2003). In addition to quantitative effects on yields, high CO2 levels and temperatures will also affect grain quality, although the impact pathways are not yet clear. One characteristic of poor grain quality is high chalk content mainly because chalky grains break during milling and thus, decrease the yield of edible rice. Rice grown in a glasshouse at 38/21°C contained more chalky grains than rice grown at 26/15°C (Lisle et al., 2000). In another experiment, either higher daytime or higher nighttime temperature alone increased the percentage of damaged rice grains (Morita et al., 2002). Filed observations in Japan indicated detrimentally affects of high temperature episodes on the grain quality of some *O. japonica* varieties (Kobayashi et al., 2007).

Climate change impacts will also impact on rice production through rising sea level rise. Observations from tide gauges indicate that the mean global sea level has risen by about 10 to 25 cm over the last 100 years, and it appears that this rise was related to the rise in global mean temperature recorded over the same period. Model projections of future global mean sea level change, based on the temperature change projections, show a rise of between 13 and 94 cm by 2100, with a central estimate of 49 cm (IPCC, 2001). Rice cultivation is the predominant form of land use in many coastal and deltaic regions of the tropics. No other crop apart from rice can be grown under these adverse conditions of unstable water levels and – in many locations – salinity. Increasing rice production in the Asian delta areas has greatly contributed to the rapid growth in global rice production and provides the bulk of rice exports from countries like Vietnam (Dawe, 2005). The delta regions in Asia have been transformed from deep water and floating rice ecosystems into irrigated rice ecosystems with improved water control provided by pumps and enlarged canal/ sluice systems. However, rising sea levels may reduce rice production in a sizable portion of the highly productive rice land in deltas. In the extensive deltas of tropical rivers, rising sea levels will have impacts reaching far inland. For instance, in the Mekong Delta high water levels will be noticeable up to the Cambodian border (Wassmann et al., 2004). Given the significance of Asian delta areas for rice exports (Dawe, 2005), rising sea levels can become major constraints to national as well as at a global rice supplies.

## 4. Climate adaptation in AFRICAN rice production

Although global rice area and production is dominated by Asian countries, African farmers have a long-standing tradition in cultivating rice for centuries. Given current growth trends, rice is likely to become the principal agricultural commodity in many parts of the continent. Rice production in SSA increased more than four times between 1961 and 2003, from about 3 million t to more than 13 million t. The increase was mainly driven by expanding rice area in SSA from 4.8 million hectares in 1987 to 8.5 million hectares in 2002. At the same time, rice yields in Africa are still at a low level. For instance, the average yield of 1.8 t/ha in 1972 increased only to 2.2 t/ha in

1997 or 1.9 t/ha in 2002. Rural poverty in the SSA region could significantly be reduced if local production were increased by 1 t $ha^{-1}$.

Rainfed lowland rice accounts for 43% of the total rice cultivated area in sub-Saharan Africa whereas irrigated rice accounts for only 14%. Thus, irrigation development should be seen as a promising means to enhance food security in Africa under climate change. In an era of diminishing land resources, future increases can only be accomplished by

- intensification of existing rice land, and
- introduction of rice cultivation into highly suitable environments.

Rice plants are very distinct from other crops because of their ability to grow in flooded environments. Flooded lowland rice systems are among the most sustainable and productive cropping systems in the world. This feature is of particular relevance for agricultural development in SSA, where upland crops like maize and cassava quickly deplete poor soils when grown with little or no fertilizer by subsistence farmers. Even when lowland rice is grown without fertilizer, it typically yields two or three times more than upland crops grown on the same soil – which can be explained by water borne nutrients as well as nitrogen-fixing bacteria and algae in the floodwater. However, the reliance on sustained floodwater renders these crops especially vulnerable to climate-related factors such as droughts as well as uncontrolled flooding and submergence.

One of the most striking characteristics of the rainfall regime in SSA is its high inter-annual as well as inter-decadal variability. A common notion is that African rainfall variability is related to an anomalous deviation of the Intertropical Convergence Zone (ITCZ). According to Nicholson (2000), this can only be observed in some of the wet years, whereas no systematic anomalous southward displacement of the ITCZ is evident in dry years. A number of influences on the variability as well as on the persistence of rainfall regimes have been identified from the results of several investigations. These include the influence of Sea Surface Temperature variations in neighboring oceans on the variability of rainfall (Bader, 2005) and the influence of biogeophysical feedback mechanisms, for example by land use change, on the persistence of a particular rainfall regime (Lare and Nicholson, 1994).

Rising temperatures are a global phenomenon, although the extent of temperature increments may vary between different regions. Recent analyses of expected temperature trends using general circulation models (GCMs) suggest that temperature increments in the SSA region will be similar to the global means. Mean surface air temperature has increased globally by about 0.5°C in the 20th century and is projected to increase by 1.4 to 5.8°C in this century. In a regional study on climate change impacts in West Africa, Jung and Kunstmann (2007) computed an annual mean temperature increase of 1.2 to 1.3°C over the next 25 years. This temperature change significantly exceeds inter-annual variability.

Over the last decades rainfall patterns in SSA have dramatically changed. Numerous climatological studies have documented decreasing rainfall amounts (coinciding with increasing temperatures) throughout West Africa (Nicholson 2000; Hulme et al., 2001 and LeBarbé et al., 2002). A striking decrease in annual rainfall in the Sahel region was observed after 1968, with a decrease of around 20 to 40% from 1931-60 to 1968-97 by Nicholson (2001). Yet, precipitation has increased for most of equatorial Africa up to 10% during the 20th century (Hulme et al., 2001). The decades of the 1970s and 1980s encompassed severe droughts in West-Africa that were exacerbated by increasing livestock density and subsequent grazing pressure (Ahrends et al., 2007). The precipitation records showed some improvement in the 1990s, but remain at a considerably lower level compared to the 1950's and 1960's. Changes in precipitation, land use, and the composition of the flora have to be regarded as proof of a widespread southward shift of the climate zones in West Africa (Wittig et al., 2007).

The current GCM scenarios predict a moderate reduction of rainfall (up to 0.5 mm $d^{-1}$) in SSA. However, rainfall predictions by GCMs are inherently less accurate than temperature prediction and show more variation in space and time. Moreover, the SSA region is also affected by the El Niño Southern Oscillation (ENSO). In an El Niño year, equatorial East Africa is wetter while Southern and West Africa are drier. In La Niña years that sometimes—but not always—follow the El Niño years, the rainfall anomalies typically go in the opposite direction. Jung and Kunstmann (2007) simulated present and future precipitation in West Africa and showed spatially explicit changes ranging from -20% to +50% (~150 to +200 mm). While the overall average indicates a small increase in precipitation, a strong temporal decrease is found for April due to a delay in the onset of the rainy season.

In recent decades, the SSA region has experienced a series of extreme precipitation events that seem to be linked to changing climate. The 2000 Mozambique flood had—apart from huge human losses—a devastating effect on the agriculture of Mozambique. Approximately 90% of the country's functioning irrigation infrastructure was damaged. Approximately 1,400 square kilometers of cultivated and grazing land was lost, leaving 113,000 small farming households with nothing in that year. In September 2007, large parts of SSA have experienced unprecedented amounts of torrential rains causing widespread flooding and enormous damage to agriculture.

SSA has long coastlines with extensive deltas, mainly in East and West Africa. Given the low financial resources and poor infrastructure in SSA countries, their coastal regions have to be considered especially vulnerable to sea level rise. For instance, Mozambique was ranked among the most vulnerable countries (1.3% land loss expected for 2100) -- following right after the small island states and even exceeding the vulnerability of countries like Bangladesh and Vietnam (Tol, 2004). Thus, rising sea levels in Africa may become an important constraint to efforts to replicate the success of the Asian green revolution, where deltas were central in boosting food supply and rice exports.

The constraints to rice production in SSA include climatic-related factors as discussed above, but also lack of infrastructure and inputs such as reliable irrigation facilities, fertilizer, as well as high post-production losses and inability to access markets. Insofar, an improved adaptation to present and future climate represents a necessary pre-requisite. Yet it should not be concealed that the success of climate adaptation programs will also depend on other measures that are beyond the scope of this review. Options to overcome constraints in SSA exist, but an integrated approach drawing on a range of production and postproduction technologies is required to achieve the increased production targets.

## 5. Climate Adaptation in SOUTH ASIAN rice production

Rice production is widely distributed in South Asia and thus, stretches over a wide range of climatic conditions across a large geographic scale and varied topography. Many regions of the sub-continent have starkly different microclimates encompassing four seasons: winter (January and February), summer (March to May), a monsoon (rainy) season (June to September), and a post-monsoon period (October to December). In contrast to Africa, climate variability of the Indian subcontinent is relatively low due to a remarkable stability in the overall amount of monsoon rainfall. Annual rainfall amounts for all India had a standard deviation of only 10%. Yet, climate variability exists;

prominent incidences were the failure of the monsoon in July 2002 and the devastating Mumbai floods of August 2005. Moreover, agriculture production is highly adapted to the regular monsoon rainfall patterns so that even small changes in this pattern translate into pronounced consequences for rice and other crops. Superimposed on the monsoon fluctuation is the question of future ENSO patterns since this affects overall atmospheric circulation in the sub-continent. ENSO effects can be observed in the form of droughts in the northern part of the Indian subcontinent during El Niño years. However, drought in India is not confined to El Niño years. In the states of Jharkhand, Orissa, and Chhattisgarh alone, rice production losses during severe droughts (about one year in five) average about 40% of total production, with an estimated value of $800 million (Pandey, 2007). In addition, flash floods can also afflict wide parts of rice production in South Asia resulting in enormous losses at a national scale (Dey and Upadhyaya, 1996).

Given the size and diversity of the sub-continent, it is difficult to make a comprehensive assessment of climate change impacts. In broad terms, the mean summer rainfall is expected to increase by about 10% for all of India by the end of the century. At the same time, South Asia will experience much larger regional and seasonal variations. The occurrence of heavy rainfall events will increase against a decrease in the number of rainy days. Temperatures will increase for all months; the hot pre-monsoon season will experience an increase of >1$^{o}$C until the time slice 2010-2039 (IPCC 2007) which is likely to result in incidences of extreme heat during the months of April and May. In the Indo-Gangetic Plain, these pre-monsoon changes will primarily affect the wheat crop, but the rice crop will also be exposed to higher temperatures in the wet season (>0.5$^{o}$C increase in time slice 2010-2039; IPCC 2007). A widely unknown impact of climate change on Indian agriculture is that of the expected melting of the Himalayan glaciers that are the main water source (up to 85% in the dry season) of the Indo-Gangetic river system. Global warming could reduce this contribution from glacier melt water to about 30% of its current level over the next 50 years. This will have major implications for water management and irrigated crop production. One of the key questions in climate change is whether the monsoon stability will remain or transform into more volatile patterns. Most models predict a modest increase in interannual variability but to differing degrees (Turner et al., 2005).

Indian food production must increase by 5 million metric tons per year to keep pace with population increase and ensure food security. Much of this extra production will need to come from rain-fed agriculture that comprises 70%

of the farmed land - but these rainfed farming systems are acutely vulnerable to climate variability and change. The evidence to date suggests that the changes in water and temperature described above will have serious consequences for agriculture.

Less rainy days and increased intensity of rainfall events will reduce the amount of water available for crop growth, given increased runoff and drainage (Challinor et al., 2004a). Changes in both the mean and the variability of temperature will also affect crop yield. Adaptation to these changes is possible: a change of crop variety can mitigate the impact of extremes (Challinor et al, 2005a), for example. Mean changes in planting date may also provide some adaptation (Mall et al., 2004), but in wide parts of the continent, e.g. the Indo-Gangetic Plain, this option will be limited by low winter temperatures. Seasonal weather forecasts could be seen as one supportive measure to optimize planting and irrigation patterns (Gadgil et al., 2002).

According to the recent IPCC assessment agricultural production in South Asia could fall by 30% by 2050 if no action is taken to combat the effects of increasing temperatures and hydrologic disruption (IPCC, 2007). For South Asia, the area-averaged annual mean warming by 2020 is projected to be between 1.0 and 1.4°C, between 2.23 and 2.87°C for 2050 and may rise by 3-4°C towards the end the 21st century. Since temperatures in the South Asian continent are already reaching critical levels during the pre-monsoon season, this further increment will reduce effectively yields of all crops including rice.

Farmers can adapt to climate change to some degree by shifting planting dates, choosing varieties with different growth duration, or changing crop rotations. However, many of these coping mechanisms may result in lower yields. In the Indo-Gangetic Plain delayed planting is already one of the major causes of reduction in crop yields–rice as well as wheat. The Indo-Gangetic Plain is one of the most populous and productive agricultural ecosystems in the world supporting 900 million people or more that 80% of the population on the Indian subcontinent. The rice-wheat cropping system is the economic backbone of this region and only a small gradual decrease in productivity in either rice or wheat crops will drastically imperil food security. The anticipated demand for rice and wheat within this region is expected to rise from current production levels of 85 and 71 million tons per year (1999-2000) to 122 and

103 million tons by 2020, respectively. Most studies project decreased yields in non-irrigated wheat and in rice, and a loss in farm-level net revenue between 9% and 25% for a temperature increase of 2–3.5°C. Aggarwal and Mall (2002) observed that a 2 °C increase resulted in a 15–17% decrease in grain yield of rice and wheat.

Sea level rise will affect the vast coastal area and flood plain zone of the Ganges-Brahmaputra and Indus Deltas. The consequences of sea level rise are (i) elevated water levels during tidal cycles and (ii) increasing cyclone frequency; both phenomena lead to increased flooding intensity as well as salt water intrusion. The combined effects of these factors will decrease agricultural production in the coastal zone of South Asia, which is dominated by rice production. However, assessments of sea level rise impacts in tropical deltas require a detailed analysis of the hydrology over the course of different seasons (Wassmann et al., 2004). Since these studies have not yet been conducted for the Ganges-Brahmaputra or Indus deltas, the impact assessment of sea level rise in South Asia relies on fairly rough estimates. In Bangladesh an increment in sea level of 45 cm would inundate 11% of the country (Warrick et al., 1996); a further increase to a 1m sea-level rise would affect 13 million people in Bangladesh, with 16% of national rice production lost (Nicholls and Leatherman 1995). A World Bank study concluded that salinity alone from a 0.3 m sea level rise will cause a net reduction of 0.5 million metric tons of rice production in Bangladesh (World Bank 2000). This additional salt water intrusion will exacerbate the ongoing degradation of land resources in the coastal areas of South Asia which is mainly driven by unsustainable shrimp cultivation. Both livelihood options of coastal communities and the natural environment of the coastal zone will be affected by the anticipated sea level rise.

## 6. Research on Climate Change Adaptation by IRRI and its partners

IRRI has a long history of studying the effect of climate on rice. Remarkably, the first experiment on temperature effects on rice was conducted one year after IRRI's inception in 1961. Probably even more remarkable, as well as prescient, the first work on high CO2 concentrations was performed in 1971. Likewise, the first workshop dealing with climate and rice dates back to 1974.

In 1991, IRRI initiated research explicitly addressing climate change impacts, namely a project funded by the United States Environmental Protection Agency (US-EPA), titled Effects of UV-B and Global Climate Change on rice, which used open-top chambers to study increased CO2 and temperature effects and included a modeling component.

In the 1990's, IRRI has also conducted extensive research on the role of rice production as a source of greenhouse gases, namely methane (e.g. Wassmann et al. 2000). More recently, IRRI has dealt with temperature effects on rice yields in several research activities, including modeling work (Sheehy et al. 2006) and analysis of high night-time temperature effects (Peng et al., 2004).

In 2007, IRRI established the Rice and Climate Change Consortium (RCCC) to assess direct and indirect consequences for rice production, to develop strategies and technologies to adapt rice to changing climate, and to explore crop management practices that reduce greenhouse gas emissions under intensive production (Wassmann et al., 2007). In the initial phase, the RCCC focus is on the improved resilience of the rice crop to heat stress. To attain this goal, the RCCC is pooling some of IRRI's research thrusts—plant breeding and plant physiology, for example—and will add new tools for screening and impact assessment. Moreover, the RCCC is now establishing monitoring sites to test the effects of emerging crop management trends to develop predictive models and guide future research Research programs on improving rice varieties are at the heartland of IRRI's mandate. A large number of completed and ongoing IRRI projects have addressed abiotic stresses like drought, submergence and salinity. In contrast, heat stress has only recently gained more attention and IRRI is currently boosting its activities in this regard. In all these projects, IRRI researchers identify the best sources of tolerant rice varieties through intensive field screening, elucidate the genetic control, and develop and test improved stress tolerant varieties under farmers' as well as under optimum management practices.

Progress in rice breeding has rapidly accelerated due to the availability of the full rice genome sequence (Matsumoto et al., 2005) and intensive QTL (quantitative trait loci) mapping efforts for a wide range of traits (Ismail et al. 2007). Despite the complexity of the traits associated with tolerance to most abiotic stresses, it has been found that tolerance to many of these stresses is controlled by a few QTLs with large effects, and that incorporation of these QTLs into high-yielding varieties could significantly help stabilize the yields of these varieties in stress-prone areas. Current efforts at IRRI and in rice breeding programs around the world are seeking to explore diverse germplasm collections and genetically dissect the causal mechanisms of tolerance to facilitate their use in breeding.

IRRI has developed a flood-tolerant rice variety using a new scientific technique called marker-assisted selection. The dissemination of such varieties and associated technologies is particularly important for the typhoon belt in Asia (e.g. Philippines, Vietnam, China). Submergence tolerance may become an increasingly important trait for rice in South Asia and Africa under ongoing climate change – as recently indicated by the widespread and unprecedented flooding in both continents.

There is also steady progress in increasing the tolerance of rice to drought and salinity stress (Ismail et al., 2007). Drought and salinity are persisting and ever-escalating problems constraining rice production in large areas of the tropics. IRRI released several improved drought tolerant materials over recent years, including breeding lines for the rainfed lowlands. Tolerant varieties outperformed popular modern varieties by more than 50% yield under drought conditions (Venuprasad et al., 2007).

Salt-affected areas are predominantly inhabited by impoverished communities with fewer opportunities for food security and livelihood options (Gregorio et al., 2002). In long stretches of coastal areas, salt intrusion renders the soil unproductive and/or unsuitable for any kind of farming. In delta areas, salinity intrusion can encroach up to 100 km inland (e.g. Mekong Delta) and rising sea levels will result in very complex hydrological effects on existing crop land (Wassmann et al., 2004). Newly released rice varieties can – within the limits set by plant physiology – better cope with higher salinity levels (Ismail et al., 2007).

IRRI's breeding efforts for rice in hot environments currently pursue three different strategies:

1. Physiological resilience: Tolerance to temperatures above 40$^{o}$C is found in germplasm from some arid environments like Southern Iran, Pakistan or Australia.
2. Reproductive patterns (daytime of flowering): Rice germplasm will be screened for genotypes that flower during early morning hours (when it is still cool).
3. Early maturity: Genotypes with short growth durations may become pivotal for avoiding exposure to unfavourable temperatures or terminal drought in areas with short rainy seasons.

The ongoing efforts by IRRI on improving abiotic stress tolerance of rice germplasm comprise conventional breeding methods such as pedigree selection based on easily identifiable morphological markers. To some extent, rice breeding can capitalize on phenotyping strategies and indicators already successfully used in breeding other crops for heat tolerance. However, molecular makers would be used to improve breeding efficiency, once suitable markers are identified from appropriate QTL-mapping/molecular genetics experiments. The overall aim is to improve ‘defensive traits’ in already popular high yielding varieties in rice growing countries.

While IRRI sees plant breeding at the heart of adaptation measures in rice production, the efficiency of this approach can significantly be increased by other efforts, including:

- Geographic analysis of vulnerable regions (where the rice crop is already experiencing critical temperature levels);
- Regional climate modeling to identify future “tilting points” of rice production (temperatures or CO2 levels above which major yield losses are experienced, for example); and
- Site-specific adjustment in crop management (shifting planting dates and improved water management, for example).

The envisaged adaptation of rice production to climate change will require substantial funds to support vigorous and concerted efforts by national and international research institutions. Climate change has recently received enormous attention in the media and policy statements -- and the adaptation of the agricultural sector was unanimously identified as the key to limiting damage.

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**Figure 1. Geographic distribution of poverty incidence and irrigated vs. rainfed rice area in South Asia and SSA (IRRI 2006)**