Rice and climate change: significance for food security and vulnerability

S. Mohanty, R. Wassmann, A. Nelson,
P. Moya, and S.V.K. Jagadish

This is an expanded version of the chapter "Rice" in Thornton P, Cramer L, editors. 2012. Impacts of climate change on the agricultural and aquatic systems and natural resources within the CGIAR's mandate. CCAFS Working Paper 23. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark. Available online at www.ccafs.cgiar.org.

IRRI

CGIAR

RESEARCH PROGRAM ON
Climate Change, Agriculture and Food Security

CCAFS

The International Rice Research Institute (IRRI) was established in 1960 by the Ford and Rockefeller Foundations with the help and approval of the Government of the Philippines. It is supported by government funding agencies, foundations, the private sector, and nongovernment organizations. Today, IRRI is one of 15 nonprofit international research centers that is a member of the CGIAR Consortium (www.cgiar.org). CGIAR is a global agricultural research partnership for a food-secure future.

IRRI is the lead institute for the CGIAR Research Program on Rice, known as the Global Rice Science Partnership (GRiSP; www.cgiar.org/our-research/cgiar-research-programs/rice-grisp). GRiSP provides a single strategic plan and unique new partnership platform for impact-oriented rice research for development.

The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS; www.ccafs.cgiar.org) is a strategic partnership of CGIAR and Future Earth, led by the International Center for Tropical Agriculture (CIAT). CCAFS brings together the world's best researchers in agricultural science, development research, climate science and Earth System science, to identify and address the most important interactions, synergies, and trade-offs between climate change, agriculture, and food security. www.ccafs.cgiar.org.

The responsibility for this publication rests with the International Rice Research Institute.

Mailing address: IRRI, DAPO Box 7777, Metro Manila, Philippines
Phone: +63 (2) 580-5600
Fax: +63 (2) 580-5699
Email: info@irri.org
Web: www.irri.org.
Rice Knowledge Bank: www.knowledgebank.irri.org
Courier address: Suite 1009, Security Bank Center
6776 Ayala Avenue, Makati City, Philippines
Tel. +63 (2) 891-1236, 891-1174, 891-1258, 891-1303

Suggested citation: Mohanty S, Wassmann R, Nelson A, Moya P, and Jagadish SVK. 2013. Rice and climate change: significance for food security and vulnerability. IRRI Discussion Paper Series No. 49. Los Baños (Philippines): International Rice Research Institute. 14 p.

ISSN 0117-8180

Contents

The importance of rice for food and nutritional security

Rice is produced in a wide range of locations and under a variety of climatic conditions, from the wettest areas in the world to the driest deserts. It is produced along Myanmar's Arakan Coast, where the growing season records an average of more than 5,100 mm of rainfall, and at Al Hasa Oasis in Saudi Arabia, where annual rainfall is less than 100 mm. World rice production is spread across at least 114 countries (FAO 2013) and rice is grown on 144 million farms worldwide—more than for any other crop. In Asia, it provides livelihoods not only for the millions of small-scale farmers and their families but also for the many landless workers who derive income from working on these farms.

Rice also dominates overall crop production (as measured by the share of crop area harvested of rice) and overall food consumption (as measured by the share of rice in total caloric intake) to a much greater extent in rice-producing Asia than elsewhere in the world.

Table 1. World rice area, yield, and production, various years.

Year	Rice, paddy		
	Area harvested (million ha)	Yield (t/ha)	Production (million tons)
1968	129.26	2.23	288.62
1973	136.57	2.45	334.93
1978	143.50	2.68	385.21
1983	142.83	3.14	448.02
1988	146.40	3.33	487.46
1993	146.49	3.62	531.00
1998	151.70	3.82	579.19
2003	148.51	3.95	587.07
2008	159.87	4.31	689.03
2009	158.51	4.32	684.60
2010	159.42	4.37	696.32

Sources: FAOSTAT online database accessed 9 January 2013.

Global rice production

Since the start of the Green Revolution, world rice production has increased markedly by almost 140% (Table 1). From 1968 to 2010, the area planted to rice increased from about 129 million hectares to about 159.4 million ha. Mean yield produced in that area almost doubled, from an average of 2.23 to 4.32 t/ha.

The world's largest rice producers by far are China and India. Although its area harvested is lower than India's, China's rice production is greater because of higher yields and because nearly all of China's rice area is irrigated, whereas less than half of India's rice area is irrigated. After China and India, the next largest rice producers are Indonesia, Bangladesh, Vietnam, Myanmar, and Thailand (Fig. 1).[1] These seven countries all had average production in 2008-10 of more than 30 million tons of paddy. The next highest country on the list, the Philippines, produced only a little more than half that. Collectively, the top seven countries account for more than 80% of world production. Although rice is grown worldwide, world rice production is dominated by "rice-producing Asia" (as thus defined by excluding Mongolia and the countries of Central Asia), which accounted for almost 91% of world rice production, on average, in 2008-10. In fact, Asia's share in global rice production has consistently remained at this high level even as early as 1961 and 1963.

In Africa, production has grown rapidly. West Africa is the main producing subregion, accounting for more than 45% of African production in 2008-10. In terms of individual countries, the leading producers of paddy (2008-10) are Egypt (5.7 million t), Nigeria (3.6 million t), and Madagascar (4.4 million t).

[1]This paragraph and the the remaining section on global production are partly adapted from Dawe et al (2010); however, the figures and numbers cited therein are updated to 2010.

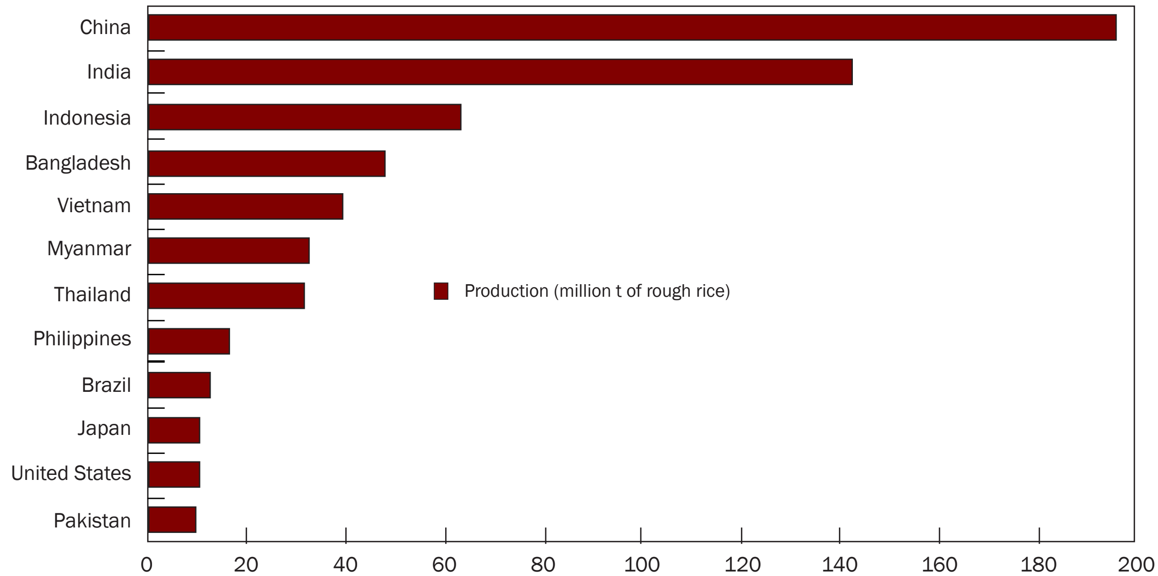


Fig. 1. Leading rice producers in the world, 2008-10.

In Latin America, Brazil is by far the largest producer, and it accounts for nearly half (45% in 2008-10) of paddy production in the region. After Brazil (12.0 million t), the largest producers are Peru and Colombia (2.9 and 2.7 million t, respectively, in 2008-10), followed by Ecuador (1.6 million t). Elsewhere, the most important production centers are in the United States (California and the southern states near the Mississippi River), which produced 9.0 million t of paddy on average in 2006-08. The leading European producers are Italy, Spain, and Russia. Australia used to be an important producer, but its output has declined substantially in recent years because of recurring drought. In Latin America and the Caribbean, rice was a preferred pioneer crop in the first half of the 20th century on the frontiers of the Brazilian Cerrado; the savannas of Colombia, Venezuela, and Bolivia; and in forest margins throughout the region.

Global rice consumption

For most rice-producing countries where annual production exceeds 1 million t, rice is the staple food (Fig. 2). In Bangladesh, Cambodia, Indonesia, Lao PDR, Myanmar, Thailand, and Vietnam, rice provides 50–80% of the total calories consumed. Notable exceptions are Egypt, Nigeria, and Pakistan, where rice contributes only 5–10% of per capita daily caloric intake.

On average, each person in the world consumes around 65 kg of rice a year, but this average hides the massive variability in consumption patterns around the world. The expanded map in Figure 3 shows an unusual view of the world where each territory has been distorted based on the proportion of the world's rice that is consumed there. The coloring in the map represents consumption per capita, so the map shows two key pieces of information that affect rice consumption patterns.[2]

Because rice-producing Asia is a net exporter of rice to the rest of the world, its current share in global rice consumption is slightly less, at about 87%. Irrespective of this, Asia has a large share of the world's population and has high rates of consumption; thus, China and India alone account for over 50% of the world's rice consumption (pie chart in Fig. 3), but they are by no means the highest consumers per capita (table in Fig. 3). Higher rates are found in much of South and Southeast Asia, West Africa, Madagascar, and Guyana. Several of these countries have per capita consumption rates surpassing 100 kg per year, and Brunei tops the table at over 20 kg per capita per month, compared with rates in Europe of less than 0.5 kg per month.

[2]This section is partly adapted from Nelson (2011).

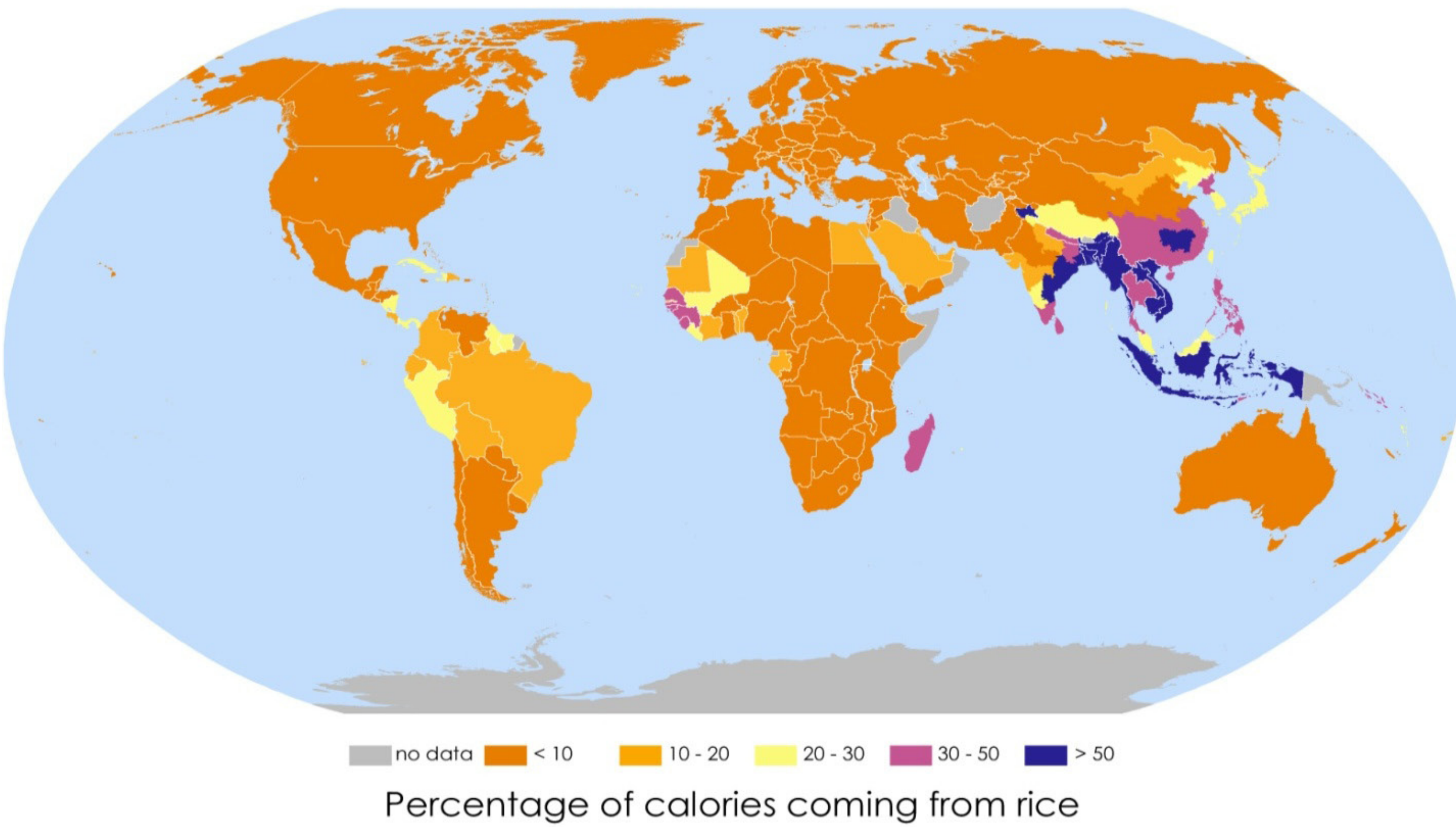
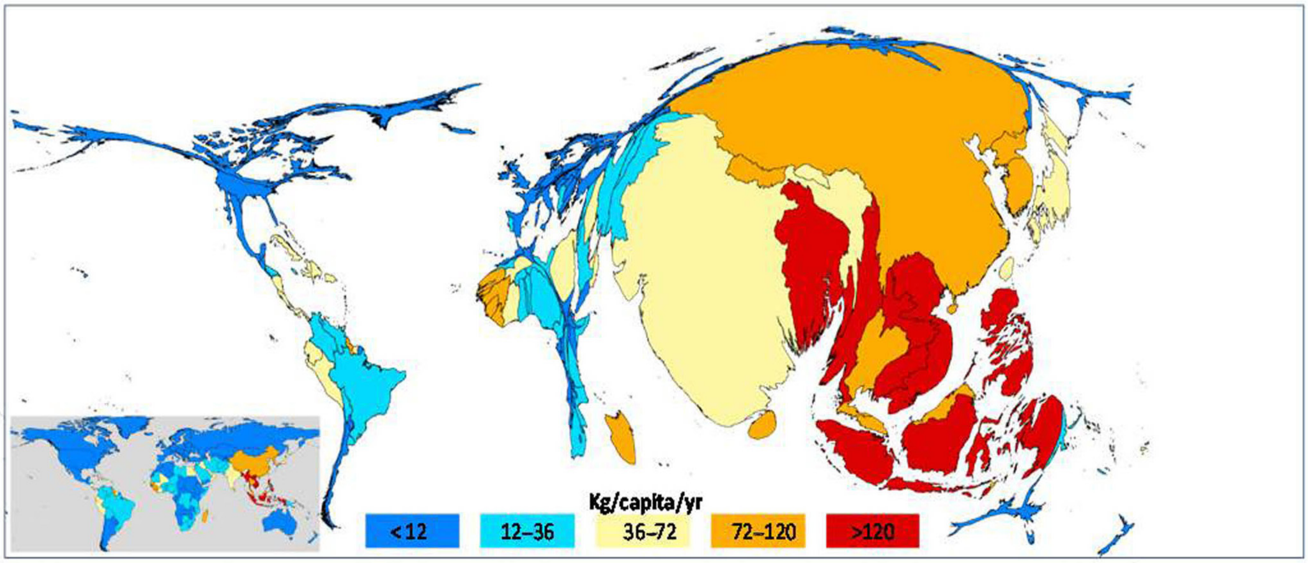
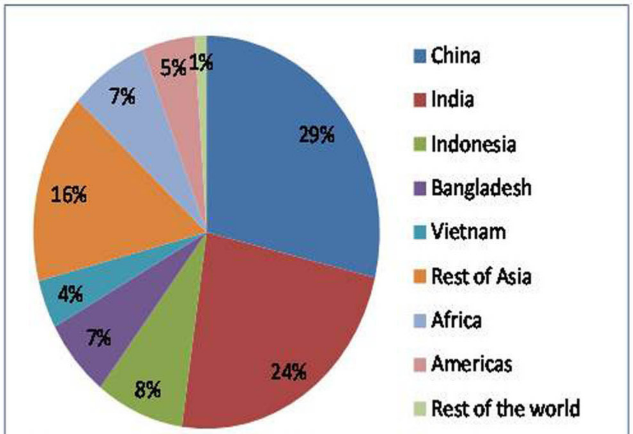


Fig. 2. Percentage of calories coming from rice. Source: Dawe et al (2010).



Territory size represents the proportion of milled rice worldwide that is consumed in that territory. Color shows the per capita consumption of milled rice. Inset map shows a more traditional representation.



Proportion of the world milled rice consumed in each region

The highest rice consuming countries in kg/capita/yr

Brunei Darussalam	245	Sri Lanka	97
Vietnam	166	Guinea	95
Laos	163	Sierra Leone	92
Bangladesh	160	Guinea-Bissau	85
Myanmar	157	Guyana	81
Cambodia	152	Nepal	78
Philippines	129	Korea, DPR	77
Indonesia	125	China	77
Thailand	103	Malaysia	77
Madagascar	102	Korea, Republic of	76

Top 20 per capita rice consuming countries

(1) Food supply quantity data from FAOSTAT - http://faostat.fao.org/site/609/DesktopDefault.aspx?PageID=609#ancor

(2) See http://www.worldmapper.org for more examples of cartograms where territories are re-sized on each map according to the subject of interest

Fig. 3. An illustration of world rice consumption.

Despite Asia's dominance in rice consumption, rice is also growing in importance in other parts of the world. In the past 50 years, per capita rice consumption has more than doubled in the rest of the world. In Africa, rice has been the main staple food (defined as the food, among the three main crops, that supplies the largest amount of calories) for at least 50 years in parts of western Africa (Guinea, Guinea-Bissau, Liberia, Sierra Leone) and for some countries in the Indian Ocean (Comoros and Madagascar). In other African countries, however, rice has displaced other staple foods because of the availability of affordable imports from Asia and rice's easier preparation, which is especially important in urban areas. In Côte d'Ivoire, for instance, the share of calories from rice increased from 12% in 1961 to 23% in 2009. In Senegal, the share increased from 20% to 29% during the same time, whereas, in Nigeria, the most populous country on the continent, it increased from 1% to 8%. Today, rice is the most important source of calories in many Latin American countries, including Ecuador and Peru, Costa Rica and Panama, Guyana and Suriname, and the Caribbean nations of Cuba, the Dominican Republic, and Haiti. It is less dominant in consumption than in Asia, however, because of the importance of wheat, maize, and beans in regional diets.

Rice consumption in the Pacific islands has increased rapidly over the past two decades. Rice, which is all imported apart from a small amount grown in Papua New Guinea, is displacing traditional starchy root crops as a major staple due to changing tastes, ease of storage and preparation, and sometimes cost. The annual national consumption of imported rice in the Solomon Islands doubled from 34 kg to 71 kg per capita during 2002-07 and tripled in Samoa (from 6 kg to 19 kg) and the Cook Islands (5 kg to 15 kg) in the same period (Rogers and Martyn 2009).

Future trends in supply and demand

As we look ahead, income growth, urbanization, and other long-term social and economic transformations are likely to influence the composition of the food basket. Normally, one would expect diversification away from rice to more high-value items such as meat, dairy products, fruits, and vegetables in the diet as income rises.

Each Asian country will be unique in the way it diversifies its consumption pattern as income rises. It is reasonable to assume that diversification away from rice will be slow in many Asian countries and the minimum threshold level of rice consumption for each country will be different.

Outside Asia, the current upward trend in rice consumption will continue, with sub-Saharan Africa (SSA) leading the pack. The growth in rice consumption in SSA so far has primarily come from the growing preference for rice among urban consumers with rising income. It is inevitable that the preference for rice will begin to grow among the rural population as economic growth becomes widespread and the rural population gets wealthier. If that happens, one could expect the growth in rice consumption to be even stronger than what has been witnessed in the past two decades.

In addition, 2 billion more people will have to be fed in the next 30 years, when the world reaches the 9 billion mark, and the population is projected to exceed 10 billion by the end of the century. If global per capita rice consumption follows the trend it has seen in the past two decades, then total consumption will grow at the rate of population growth. Seck et al (2012) project global rice consumption to rise from 439 million t (milled rice) in 2010 to 496 million tons in 2020 and further increase to 555 million t in 2035. According to this study, Asian rice consumption is projected to account for 67% of the total increase from 388 million t in 2010 to 465 million t in 2035. As expected, Africa tops the chart in terms of percentage increase in total consumption, with an increase of 130% from 2010 rice consumption. In the Americas, total rice consumption is projected to rise by 33% during the same period.

On the supply side, the annual rice yield growth rate has dropped to less than 1% in recent years compared with 2–3% during the Green Revolution period of 1967-90. Current rice area is at an all-time high and increasing rice production through area expansion in the future is highly unlikely in most parts of the world because of water scarcity and competition for land from nonagricultural uses such as industrialization and urbanization. Thus, it is prudent to assume that additional production will have to come entirely from yield growth. In that case, annual yield growth of 1.2–1.5% will be needed compared with current yield growth of less than 1% to keep rice affordable to millions of poor people in the world.

Biological vulnerability to climate change

Introduction

Rice, with its wide geographic distribution extending from 50°N to 35°S, is expected to be the cultivated crop most vulnerable to future changing climates. Rice is sensitive to different abiotic stresses that will be exacerbated with more climate extremes under climate change:

- High temperatures coinciding with critical developmental stages
- Floods causing complete or partial submergence
- Salinity, which is often associated with sea-water inundation
- Drought spells that are highly deleterious to rainfed systems

Plant breeding has a proven track record of improving tolerance of these abiotic stresses, in particular, since new molecular tools such as marker-assisted backcrossing became available to speed up the introgressing of tolerance genes. Selected high-yielding rice varieties have now been further developed to cope with individual stresses—a process that is likely to be continued to cover the major mega-varieties that are affected by individual stresses. However, these climate-induced extremes often appear in combination, that is, salinity is frequently accompanied by submergence in coastal rice systems. The major bottleneck for combined tolerance of different stresses is the lack of a thorough understanding of the complex genotype × environment (G × E) interaction that may adversely affect the reciprocal development of traits.

High temperatures

Temperatures beyond critical thresholds not only reduce the growth duration of the rice crop but also increase spikelet sterility, reduce grain-filling duration, and enhance respiratory losses, resulting in lower yield and lower quality rice grain (Fitzgerald and Resurreccion 2009, Kim et al 2011). Rice is relatively more tolerant of high temperatures during the vegetative phase but is highly susceptible during the reproductive phase, particularly at the flowering stage (Jagadish et al 2010). Unlike other abiotic stresses, heat stress occurring during either the day or night has differential impacts on rice growth and production. Recently, high night temperatures having a greater negative effect on rice yield have been documented, with 1 °C above critical temperature (>24 °C) leading to a 10% reduction in both grain yield and biomass (Peng et al 2004, Welch et al 2010). With the rapid increase in the minimum (nighttime) temperature during the past two to three decades compared with the maximum (daytime) temperature, and this is predicted to continue in the same trend, the impact could be felt on a global scale, which, for now, is happening in select vulnerable regions.

High day temperatures in some tropical and subtropical rice-growing regions are already close to the optimum levels, and an increase in intensity and frequency of heat waves coinciding with the sensitive reproductive stage can result in serious damage to rice production. In 2003, extreme high day temperature episodes along the Yangtze River in China resulted in an estimated 3 million ha of rice damaged, resulting in a loss of about 5.18 million t of paddy rice (Xia and Qi 2004, Yang et al 2004); similar losses were recorded in 2006 and 2007 (Zou et al 2009). Japan recorded unusual temperatures of >40 °C coinciding with flowering in many areas of the Kanto and Tokai regions during the summer season of 2007, resulting in 25% yield losses (Hasegawa et al 2009). Similar reports have emerged from different hot and vulnerable regions of Asia, including Pakistan, Bangladesh, and Vietnam.

Recent research points to a significant interaction of high temperatures with relative humidity, with higher humidity accompanied by moderate to high temperatures having a more pronounced negative impact than conditions with lower relative humidity (Weerakoon et al 2008). On the basis of the interaction between high temperature and high relative humidity, rice cultivation regions in the tropics and subtropics can be classified into hot/dry or hot/humid regions. It can be confidently assumed that rice cultivation in hot/dry regions where temperatures may exceed 40 ^{o}C (e.g., Pakistan, Iran, India) has been facilitated through unintentional selection for efficient transpiration cooling (an avoidance mechanism) under a sufficient supply of water. With erratic rainfall patterns and increasing pressure on irrigation water, this adaptive trait would become less functional, hence, drastically increasing the vulnerability of rice in the most productive regions such as Egypt, Australia, etc. Therefore, developing rice varieties that can withstand both high day and night temperatures under varying amounts of humidity is vitally important.

Floods

Floods are a significant problem for rice farming, especially in the lowlands of South and Southeast Asia. Since there are no alternatives, subsistence farmers in these areas depend on rice, which—in contrast to other crops—thrives under shallow flooding. However, yield losses are attributed to unpredictable flood events, which can be grouped into three damage mechanisms:

- Complete submergence (often referred to as "flash flooding") causing plant mortality after a few days
- Partial submergence over longer time spans (often referred to as "stagnant flooding") triggers substantial yield losses
- Waterlogging in direct-seeded rice creates anaerobic conditions that impair germination

Complete or partial submergence is an important abiotic stress that affects 10–15 million ha of rice fields in South and Southeast Asia, causing yield losses estimated at US$1 billion every year (Dey and Upadhyaya 1996). This number is anticipated to increase considerably in the future given the increase in sea-water level, as well as an increase in frequencies and intensities of flooding caused by extreme weather events (Bates et al 2008).

Although a semiaquatic plant, rice is generally intolerant of complete submergence and plants die within a few days when completely submerged. Traditionally, flood-prone areas along the big rivers of South and Southeast Asia have been growing deepwater rice. This type of rice plant escapes complete submergence by rapid internode elongation that pushes the plants above the water surface, where they have access to oxygen and light to resume their mitochondrial oxidative pathway and photosynthesis. However, low yield potential and long maturity duration have led to the replacement of deepwater rice by short-maturity varieties grown in the seasons before and after peak flooding. Moreover, flood-tolerant rice varieties had already been identified in the 1970s (Vergara and Mazaredo 1975) and have been used as donors of tolerance by breeders, and studies have been made on tolerance mechanisms ever since. Although conventionally bred varieties were characterized by poor grain quality and poor agronomic traits, new molecular approaches brought about high-yielding varieties with the *SUB1* gene responsible for conveying flood tolerance (Xu et al 2006).

The most common problem in flood-prone areas is "flash flooding." It can completely submerge rice fields for up to 2 weeks at any time during the season and this often occurs more than once.

Another type of flooding stress is stagnant flooding, which is characterized by prolonged partial flooding without submerging the plants completely (Septiningsih et al 2009, Mackill et al 2010, Singh et al 2011). In contrast to the tolerance mechanism of *SUB1*, stagnant flooding requires plants to have facultative elongation ability to keep up with the constant rise of the water surface. Improved breeding lines that are tolerant of submergence followed by stagnant flooding have been developed by IRRI (Mackill et al 2010) and are expected to be adopted in large areas of rainfed lowlands, where the two types of flooding coexist.

Anaerobic germination is a particular problem under direct seeding, an emerging technology in both rainfed and irrigated rice ecosystems. Heavy rainfall right after sowing inevitably causes waterlogging in fields that are poorly drained and/or leveled. As a consequence, the seeds drown and are unable to germinate normally, resulting in poor crop establishment and low yield. Developing varieties with early seedling vigor in anaerobic conditions can provide a safety net for small farmers. Additionally, shallow flooding right after sowing helps suppress weed infestation, a major challenge in direct-seeding practices.

Salinity

Rice can be categorized as a moderately salt-sensitive crop with a threshold electrical conductivity of 3 dS/m (Maas and Hoffman 1977). Yet, growing rice is the only option for crop production in most salt-affected soils. The reason for this counterintuitive advantage of the rice crop in saline areas is that rice thrives well in standing water, which, on the other hand, helps leach salts from the root zone to lower layers. Similar to drought tolerance, salt stress response in rice is complex and varies with the stage of development. Rice is relatively more tolerant during germination, active tillering, and toward maturity but is sensitive during the early vegetative and reproductive stages (Moradi et al 2003, Singh et al 2008). Salinity tolerance seems to involve numerous traits, some of which are more or less independent (Moradi and Ismail 2007, Ismail et al 2007). Most salt-tolerant landraces are low-yielding with many undesirable traits. Hence, a precision marker-assisted breeding approach is employed to rapidly transfer tolerance genes from traditional varieties into high-yielding breeding lines (Thomson et al 2010).

The increasing threat of salinity has become an essential concern linked to the consequences of climate change. As an indirect effect of increased temperature on sea-level rise, much larger areas of coastal wetlands may be affected by flooding and salinity in the next 50 to 100 years (Allen et al 1996). Sea-level rise will increase salinity encroachment in coastal and deltaic areas that have previously been favorable for rice production (Wassmann et al 2004). Furthermore, 55% of total groundwater is naturally saline (Ghassemi et al 1995). Secondary salinization, specifically due to the injudicious use of water and fertilizer in irrigated agriculture, could increase the percentage of brackish groundwater. The groundwater table, if it rises and if it is brackish in nature, becomes ruinous to most of the vegetation. Higher temperature aggravates the situation by excessive deposition of salt on the surface due to capillary action, which is extremely difficult to leach below the rooting zone.

Drought

Drought stress is the most important constraint to rice production in rainfed systems, affecting 10 million ha of upland rice and over 13 million ha of rainfed lowland rice in Asia alone (Pandey et al 2007). The 2002 drought in India could be described as a catastrophic event, as it affected 55% of the country's area and 300 million people. Rice production declined by 20% from the interannual baseline trend (Pandey et al 2007). Similarly, the 2004 drought in Thailand affected more than 8 million people in almost all provinces. Severe droughts generally result in starvation and impoverishment of the affected population, resulting in production losses during years of complete crop failure, with dramatic socioeconomic consequences on human populations (Pandey et al 2007). Production losses to drought of milder intensity, although not so alarming, can be substantial. The average rice yield in rainfed eastern India during "normal" years still varies between 2.0 and 2.5 t/ha, far below achievable yield potentials. Chronic dry spells of relatively short duration can often result in substantial yield losses, especially if they occur around flowering stage. In addition, drought risk reduces productivity even during favorable years in drought-prone areas because farmers avoid investing in inputs when they fear crop loss. Inherent drought is associated with the increasing problem of water scarcity, even in traditionally irrigated areas, due to rising demand and competition for water uses. This is, for instance, the case in China, where the increasing shortage of water for rice production is a major concern, although rice production is mostly irrigated (Pandey et al 2007).

Water stress in rice production arises from the higher frequency of El Niño events and reductions in the number of rainy days (Tao et al 2004), but is also coupled with increasing temperatures (and higher evapotranspiration). Because of its semiaquatic phylogenetic origins and the diversity of rice ecosystems and growing conditions, current rice production systems rely on an ample water supply and thus are more vulnerable to drought stress than other cropping systems (O'Toole 2004). At the whole-plant level, soil water deficit is an important environmental constraint influencing all the physiological processes involved in plant growth and development. Drought is conceptually defined in terms of rainfall shortage vis-à-vis a normal average value in the target region. However, drought occurrence and effects on rice productivity depend more on rainfall distribution than on total seasonal rainfall. Beyond the search for global solutions to a generic "drought," the precise characterization of droughts in the target population of environments is a prerequisite for better understanding their consequences for crop production (Heinemann et al 2008).

In Asia, more than 80% of the developed freshwater resources are used for irrigation purposes, mostly for rice production. Thus, even a small savings of water due to a change in current practices will translate into a significant reduction in the total consumption of fresh water for rice farming. By 2025, 15–20 million ha of irrigated rice will experience some degree of water scarcity (Bouman et al 2007). Many rainfed areas are already drought-prone under present climatic conditions and are likely to experience more intense and more frequent drought events in the future.

Thus, water-saving techniques are absolutely essential for sustaining—and possibly increasing—future rice production under climate change. The period of land preparation encompasses various options to save water, namely, lining of field channels, land leveling, improved tillage, and bund preparation. Likewise, crop establishment can be optimized under water scarcity by direct seeding, which reduces the turnaround time between crops and may tap rainfall. Finally, the crop growth period offers essentially three alternative management practices to save irrigation water: saturated soil culture (SSC), alternate wetting and drying (AWD), and aerobic rice.

Multiple stresses

Abiotic stresses such as heat, drought, submergence, and salinity are the major factors responsible for significant annual rice yield losses. However, they often occur in combination in farmers' fields, causing incremental crop losses (Mittler 2006). An example of successive flood/drought exposure within one season occurred in Luzon, Philippines, in 2006. During the wet-season crop, seasonal rainfall exceeded 1,000 mm, including a major typhoon (international name: Xangsane) with around 320 mm of rainfall in a single day. Yet, a short dry spell that coincided with the flowering stage resulted in a dramatic decrease in grain yield and harvest index compared to the irrigated control (Serraj et al 2009). Similarly, Wassmann et al (2009) reported that high-temperature stress during the susceptible/critical flowering to early grain-filling period coincided with drought stress in Bangladesh, eastern India, southern Myanmar, and northern Thailand. For example, in Bangladesh, rice is grown in large areas during the "boro" season (dry season, December to April), with temperatures ranging from 36 to 40 ^{o}C during the critical flowering stage. Hence, with the frequency of high temperatures during crop growing seasons predicted to increase in many areas, drought exacerbated by heat stress will have serious implications for future rice production in drought-prone areas (Battisti and Naylor 2009).

Breeding for tolerance of abiotic stresses has typically been pursued individually. A novel "stress combination matrix" has illustrated the interactions between different abiotic stresses such as heat and drought, and heat and salinity (Mittler 2006). The combined stress increased the negative effect on crop production. For example, in response to heat stress, plants open their stomata to maintain a cooler canopy microclimate through transpiration, but, under combined heat and drought stress, the sensitive stomata are closed to prevent loss of water, which further increases canopy/tissue temperatures (Rizhsky et al 2002, 2004). A similar phenomenon occurs under combined heat and salinity stress (Moradi and Ismail 2007). It was thus concluded that the study of abiotic stress combinations involves a "new state of abiotic stress" rather than just a sum of two different stresses (Mittler 2006). Therefore, the need to develop crop plants with high tolerance for a combination of stresses is advocated. In support of this hypothesis, recent research has highlighted physiological, biochemical, and molecular connections between heat and drought stress (Barnabas et al 2008, Rang et al 2011).

Socioeconomic vulnerability to climate change

Sustainable growth in rice production worldwide is needed to ensure food security, maintain human health, and sustain the livelihoods of millions of small farmers. This is because rice is the major staple crop of nearly half of the world's population (Zeigler and Barclay 2008, Khush 2004) and more than 100 million households in Asia and Africa depend on rice cultivation as their primary source of income and employment (FAO 2004, cited by Redoña 2004). Moreover, rice is the source of 27% of dietary energy and 20% of dietary protein in the developing world (Redoña 2004). About 90% of the total rice grown in the world is produced by 200 million smallholder farmers (Tonini and Cabrera 2011). Importantly, because of the increases in population and income in major rice-consuming countries, demand for rice has been steadily increasing over the years. Mohanty (2009) estimated that the global demand for rice will increase by about 90 million t by 2020.

One of the most serious long-term challenges to achieve sustainable growth in rice production is climate change (Vaghefi et al 2011, Wassmann and Dobermann 2007, Adams et al 1998, IFPRI 2010). Rice productivity and sustainability are threatened by biotic and abiotic stresses, and the effects of these stresses can be further aggravated by a dramatic change in global climate. By 2100, the mean surface temperature of the Earth is expected to rise by 1.4 to 5.8 ^oC and extreme events, such as floods, droughts, and cyclones, are likely to become more frequent (IPCC 2007). In delta/coastal regions, climate change is expected to raise sea levels, and this will increase the risk of flooding and salinity problems in major rice-growing areas (Wassmann et al 2004, Mackill et al 2010b).

These predicted changes in climate are likely to further increase the economic vulnerability of poor rice producers, particularly in South Asia, where more than 30% of the population is extremely poor (with income of less than US$1.25 per day). For example, rice yields will be severely affected by the increase in temperature of the Earth due to the atmospheric concentration of carbon dioxide (Peng et al 2004). Rice yield is found to be more sensitive to nighttime temperature: each 1 ^oC increase in nighttime temperature leads to a decline of about 10% in rice yield (Peng et al 2004, Welch et al 2010). Furthermore, droughts and floods already cause widespread rice yield losses across the globe (e.g., Pandey et al 2007, IRRI 2010, IFAD 2009, Pandey and Bhandari 2007), and the expected increase in drought and flood occurrence due to climate change would exacerbate rice production losses in the future.

Drought, which is generally defined as a situation in which actual rainfall is significantly below the long-run average for the area, is a chronic problem that affects about 38% of the world's area. This area affected by drought is inhabited by nearly 70% of the total world population and produces 70% of the total agricultural output in the world (Dilley et al 2005). In Asia, approximately 34 million ha of shallow rainfed lowland rice farms and 8 million ha of upland rice farms, or one-third of the total Asian rice area (Huke and Huke 1997), are subject to occasional or frequent drought stress (Venuprasad et al 2008). The estimated economic costs of these drought events are enormous. In India, around 70% of the upland rice area is drought-prone. Drought accounts for approximately 30% of average annual upland rice yield losses, or about 1.28 million t (Widawsky and O'Toole 1990). Pandey et al (2007), using historical information, demonstrate that there is a strong link between drought and famines in Asia and Africa over the decades. In India, major droughts in 1918, 1957, 1958, and 1965 resulted in major famines that affected millions of people (FAO 2001, cited in Pandey et al 2007). Similarly, the 2004 drought in Thailand caused major damage to about 2 million ha of rice land and affected 8 million people (Bank of Thailand 2005, Asia Times 2005).

Flood is another notorious abiotic stress that regularly causes severe rice yield damage, not only on deepwater rice farms but also on lowland rice farms. Deepwater rice and rainfed lowland rice are frequently hit by flash floods caused by monsoon rain and this results in substantial yield losses every year. Since deepwater rice and lowland rice comprise nearly 33%

of the world's rice-growing area (Bailey-Serres et al 2010), flood is a major source of production losses in these important rice ecosystems. Often, transient flash flood occurs and is followed by longstanding stagnant floods. This type of flood reduces the survival chance of rice plants and causes severe damage to rice yields. For example, rice production losses in Bangladesh and India due to flash floods are estimated to be around 4 million t per year, and this lost production (had there been no floods) could have fed 30 million people (IRRI 2010). One important thing to note is that rainfed lowland rice production areas are also exposed to drought and are thus prone to the "twin" problems of drought and flood. Therefore, having newer varieties and technologies that can mitigate the effects of both droughts and floods is very important for these regions.

Considering future changes in the global climate, Mottaleb et al (2012) examine the net economic benefit of developing and disseminating a combined drought- and flood-tolerant rice variety in South Asia using an *ex ante* impact assessment framework, partial equilibrium economic models, and the crop growth simulation model ORYZA2000 (Bouman et al 2001). The study shows that the new drought- and flood-tolerant variety would result in an average yield advantage that is 2.88% higher than the base case had this particular variety been developed and disseminated in South Asia (for this period). Based on the estimates from ORYZA2000, the study calculated economic surplus and obtained the return on research investment (e.g., net present value and internal rate of return). The estimated cumulative net benefits of a combined drought- and flood-tolerant variety that is released in 2016 (for the period 2011-50 and discount rate at 5%) are $1.2 billion for India, $535 million for Bangladesh, $80 million for Nepal, and $22 million for Sri Lanka. For the large open economy model considering the whole of South Asia, the estimated net benefits from research investments and dissemination of a combined drought- and flood-tolerant variety are $1.8 billion. Overall, the economic welfare of producers and consumers in South Asia is improved with the development and release of a combined drought- and flood-tolerant variety.

Mottaleb et al (2012) also demonstrates that, in 2035, rice production and consumption would be higher and retail prices in South Asian countries would be lower if a drought- and flood-tolerant rice variety were developed and released in the region (as compared to the case in which the variety was not developed and released). Mottaleb et al (2012) show that the percentage increase in production (relative to the baseline) ranges from 3.01% in India to 5.38% in Nepal. It also shows that rice prices in South Asian countries will be lower if a drought- and flood-tolerant variety is developed and released as compared to the baseline case in which the new variety is not developed. Our estimates suggest that retail prices in India, for example, would be about 22% higher if the variety is not developed and released in the region. Similar price effects can also be observed for the other South Asian countries in the study, albeit the magnitudes of the price effects are somewhat smaller (compared to India). The price reduction effect observed here implies that poor rice consumers (especially in urban areas) would benefit from the release of a drought- and flood-tolerant variety in South Asia. Lower prices would make rice more affordable to poor people and could lead to improved nutritional outcomes. Finally, Mottaleb et al (2012) demonstrate that the economic benefits of a combined drought- and flood-tolerant rice variety more than outweigh the cost of developing this new variety, especially in light of global climate change. The development and release of this new variety in South Asia would provide a net economic benefit of about $1.8 billion for South Asia alone.

Considering that changes in the global climate will result in more extreme events, such as floods, droughts, and cyclones, substantial economic benefits can be achieved from the development of an improved rice variety that is more resilient to climate change. This type of technology would allow rice producers to adapt to worsening global climate and allow them to mitigate the adverse effects of climate change in the future. In the long run, the returns to the investment of developing this particular "climate change-tolerant" variety would be high. Otherwise, poor rice farmers in the developing South Asian region might be much vulnerable and food security in the region might be at stake if a new multiple stress-tolerant variety of rice is not available in the near future.

References

Adams RM, Hurd BH, Lenhart S, Leary N. 1998. Effects of global climate change on agriculture: an interpretative review. Climate Res. 11 (December):19-30. Online at www.int-res.com/articles/cr/11/c011p019.pdf, accessed on 12 Nov. 2011.

Allen JA, Pezeshki SR, Chambers JL. 1996. Interaction of flooding and salinity stress on baldcypress (*Taxodium distichum*). Tree Physiol. 16:307-313.

Asia Times. 2005. Grim reaping for Thai farmers: a news on Southeast Asia. Hong Kong (China): Asia Times Online Co., Ltd. Online at www.atimes.com, accessed on 29 April 2005, cited in Pandey S, Bhandari H, Hardy B, editors. 2007. Economic costs of drought and rice farmers' coping mechanisms: a cross-country comparative analysis. Los Baños (Philippines): International Rice Research Institute.

Bailey-Serres J, Fukao T, Ronald P, Ismail A, Heuer S, Mackill D. 2010. Submergence tolerant rice: *SUB1*'s journey from landrace to modern cultivar. Rice 3(2-3):138-147. Online at www.springerlink.com/content/e6j4563076r5h723/, accessed on 12 Nov. 2011.

Bank of Thailand. 2005. The inflation report, January 2005. Bangkok (Thailand): The Bank of Thailand. p 95, cited in Pandey S, Bhandari H, Hardy B, editors. 2007. Economic costs of drought and rice farmers' coping mechanisms: a cross-country comparative analysis. Los Baños (Philippines): International Rice Research Institute.

Barnabás B, Jäger K, Fehär A. 2008. The effect of drought and heat stress on reproductive processes in cereals. Plant Cell Environ. 31:11-38.

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP, editors. 2008. Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva. www.ipcc.ch/ipccreports/tp-climate-change-water.htm. 210 p.

Battisti DS, Naylor RL. 2009. Historical warnings of future food insecurity with unprecedented seasonal heat. Science 323:240-244. doi:10.1126/ science.1164363.

Bouman BAM, Humphreys E, Tuong TP, Barker R. 2007. Rice and water. Adv. Agron. 92:187-237.

Bouman BAM, Kropff MJ, Tuong TP, Wopereis MCS, ten Berge HFM, Van Laar HH. 2001. ORYZA 2000: modeling lowland rice. Los Baños (Philippines): International Rice Research Institute.

Dawe D, Pandey S, Nelson A. 2010. Emerging trends and spatial patterns of rice production. In: Pandey S, Byerlee D, Dawe D, Dobermann A, Mohanty S, Rozelle S, Hardy B, editors. Rice in the global economy: strategic research and policy issues for food security. Los Baños (Philippines): International Rice Research Institute. p 15-35.

Dey M, Upadhyaya H. 1996. In: Rice research in Asia: progress and priorities. Evenson R, Herdt R, Hossain M, editors. Oxon, (UK): CAB International, p. 291-303.

Dilley M, Chen RS, Deichmann U, Lerner-Lam AL, Arnold M, Agwe J, Buys P, Kjekstad O, Lyon B, Yetman G. 2005. Natural disaster hotspots: a global risk analysis. Washington, D.C. (US): Hazard Management Unit, World Bank. Online at http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1144073945012/Arnold.pdf, accessed on 12 Nov. 2011.

FAO (Food and Agriculture Organization of the United Nations). 2001. Report of the Asia-Pacific Conference on Early Warning, Prevention, and Preparedness and Management of Disasters in Floods and Agriculture. Chiang Mai, Thailand, 12-15 June 2001. Bangkok (Thailand): FAO Regional Office for Asia and the Pacific (RAP). Publication No. 2001/14. Bangkok (Thailand): FAO/RAP.

FAO STAT online database. January 2013.

Fitzgerald MA, Resurreccion AP. 2009: Maintaining the yield of edible rice in a warming world. Funct. Plant Biol. 36:1037-1045.

Ghassemi F, Jakeman AJ, Nix HA. 1995. Salinisation of Land and Water Resources. Wallingford (UK): CAB International.

GRiSP. (Global Rice Science Partnership). 2013. Rice Almanac 4th edition (forthcoming).

Hasegawa T, Kuwagata T, Nishimori M, Ishigooka Y, Murakami M, Yoshimoto M, Kondo M, Ishimaru T, Sawan S, Masaki Y, Matsuzaki H. 2009. Recent warming trends and rice growth and yield in Japan. MARCO Symposium on Crop Production under Heat Stress: Monitoring, Impact Assessment and Adaptation. Tsukuba, Japan.

Heinemann AB, Dingkuhn M, Luquet D, Combres JC, Chapman S. 2008. Characterization of drought stress environments for upland rice and maize in central Brazil. Euphytica 162:395-410.

Huke RE, Huke EH. 1997. Rice area by type of culture, South, Southeast, and East Asia: a revised and updated database. Los Baños (Philippines): International Rice Research Institute.

IFAD (International Fund for Agricultural Development). 2009. Drought, coping mechanisms and poverty: insights from rainfed rice farming in Asia. The seventh in a series of discussion papers produced by the Asia and the Pacific Division, Rome: International Fund for Agricultural Development.

IPCC (Intergovernmental Panel of Climate Change). 2007. Fourth Assessment Report of the Intergovernmental Panel on Climate Change: The Impacts, adaptation and vulnerability (working group III). New York: Cambridge University Press, UK and USA.

IFPRI (International Food Policy Research Institute). 2010. Food security, farming and climate change to 2050. Scenarios, results and policy options. Washington, D.C.: (US) International Food Policy Research Institute. Online: www.ifpri.org/sites/default/files/publications/ib66.pdf, accessed on 30 Nov. 2011.

IRRI (International Rice Research Institute). 2010. Scuba rice: breeding flood-tolerance to Asia's local mega rice varieties. Los Baños (Philippines): International Rice Research Institute. Online: www.eiard.org/media/uploads/documents/case_studies/dfid_impact_case_study_sub1_rice_-_may_2010.pdf, accessed on 20 Nov. 2011.

Ismail AM, Heuer S, Thomson MJ, Wissuwa M. 2007. Genetic and genomic approaches to develop rice germplasm for problem soils. Plant Mol. Biol. 65:547-570.

Jagadish SVK, Muthurajan R, Oane R, Wheeler TR, Heuer S, Bennett J, Craufurd PQ. 2010: Physiological and proteomic approaches to dissect reproductive stage heat tolerance in rice (*Oryza sativa* L.). J. Exp. Bot. 61:143-156.

Khush GS. 2004. Harnessing science and technology for sustainable rice based production system. Paper presented at the Conference on Rice in Global Markets and Sustainable Production Systems, 12-13 February 2004. Rome (Italy): Food and Agriculture Organization of the United Nations (FAO). Online: www.fao.org/rice2004/en/pdf/khush.pdf, accessed on 12 December 2011.

Kim J, Shon J, Lee CK, Yang W, Yoon Y, Yang WH, Kim YG, Lee BW. 2011. Relationship between grain filling duration and leaf senescence of temperate rice under high temperature. Field Crops Res. 122(3): 207-213 doi: 10.1016/j.fcr.2011.03.014.

Maas EV, Hoffmann GJ. 1977. Crop salt tolerance: current assessment. J. Irrig. Drain. Div. ASCE. 103:115-134.

Mackill DJ, Ismail AM, Kumar A, Gregorio GB. 2010b. The role of stress-tolerant varieties for adapting to climate change. Paper from the CURE Workshop on Climate Change, 4 May 2010, Siem Reap, Cambodia. Online: http://irri.org/climatedocs/presentation_Lists/Docs/5_Mackill.pdf, accessed on November 15, 2011.

Mackill, DJ, Ismail AM, Pamplona AM, Sanchez DL, Carandang JJ, Septiningsih EM. 2010a. Stress-tolerant rice varieties for adaptation to a changing climate. Crop Environ. Bioinformatics 7:250-259.

Mills FB. 1998. Ex-ante research evaluation and regional trade flows: maize in Kenya. J. Agric. Econ. 49(3):393-408.

Mittler R. 2006. Abiotic stress: the field environment and stress combination. Trends Plant Sci. 11(1):15-19.

Mohanty S. 2009. Rice and the global financial crisis. Rice Today 8(1):40.

Moradi F, Ismail A. M, Gregorio G, Egdane J. 2003. Salinity tolerance of rice during reproductive development and association with tolerance at seedling stage. Indian J. Plant Physiol. 8:105-116.

Moradi F, Ismail AM. 2007. Responses of photosynthesis, chlorophyll fluorescence, and ROS scavenging system to salt stress during seedling and reproductive stages in rice. Ann. Bot. 99:1161-1173.

Mottaleb KA, Rejesus RM, Mohanty S, Murty MVR, Li T, Valera HG, Gumma MK. 2012. *Ex* ante assessment of a combined drought- and submergence-tolerant rice variety in the presence of climate change. Paper presented at the Agricultural & Applied Economics Association Annual Meeting, Seattle, Washington, USA, 12-14 August. Los Baños (Philippines): International Rice Research Institute. Online: http://ageconsearch.umn.edu/bitstream/124745/2/MottalebRev.pdf

Nelson A. 2011. Who eats the most rice? Rice Today 10(4):44-45

O'Toole TC. 2004. Rice water: the final frontier. In: First International Conference on Rice for the Future, 31 Augst.-2 Sept. 2004. Bangkok, Thailand.

Pandey S, Bhandari H. 2007. Drought: an overview. In: Pandey S, Bhandari H, Hardy B, editors. Economic costs of drought and rice farmers' coping mechanisms: a cross-country comparative analysis. Los Baños (Philippines): International Rice Research Institute. p. 11-30.

Pandey S, Bhandari H, Hardy B, editors. 2007. Economic costs of drought and rice farmers' coping mechanisms: a cross-country comparative analysis. Los Baños (Philippines): International Rice Research Institute. 203 pp.

Peng SB, Huang JL, Sheehy JE, Laza RC, Visperas RM, Zhong XH, Centeno GS, Khush GS, Cassman KG. 2004. Rice yields decline with higher night temperature from global warming. Proc. Natl. Acad. Sci. 101:9971-9975.

Rang ZW, Jagadish SVK, Zhou QM, Craufurd PQ, Heuer S. 2011. Effect of heat and drought stress on pollen germination and spikelet fertility in rice. Environ. Exp. Bot. 70:58-65. doi:10.1016/ j.envexpbot.2010.08.009.

Redoña ED. 2004. Rice biotechnology for developing countries in Asia. In: Eaglesham A. Agricultural biotechnology: finding common international goals. National Agricultural Biotechnology Council (NABC) Report No. 16. Ithaca (New York): National Agricultural Biotechnology Council. Online: http://nabc.cals.cornell.edu/pubs/nabc_16/nabc_16.pdf, accessed on 20 Dec. 2011.

Rizhsky LL, Hongjian, Mittler R. 2002. The combined effect of drought stress and heat shock on gene expression in tobacco. Plant Physiol. 130:1143-1151.

Rizhsky L, Liang H, Shuman J, Shulaev V, Davletova S, Mittler R. 2004. When defense pathways collide: the response of Arabidopsis to a combination of drought and heat stress. Plant Physiol. 134:1683-1696.

Rogers TS, Martyn T. 2009. Background Paper: Food. Pacific Economic Survey 2009. FAO.

Seck PA, Digna A, Mohanty S, Wopereis M. 2012. Crops that feed the world. 7. Rice. Food Security 4:7-24.

Septiningsih EM, Pamplona AM, Sanchez DL, Neeraja CN, Vergara GV, Heuer S, Ismail AM, Mackill DJ. 2009. Development of submergence-tolerant rice cultivars: the Sub1 locus and beyond. Ann. Bot. 103:151-160

Serraj R, Kumar A, McNally KL, Slamet-Loedin I, Bruskiewich R, Mauleon R, Cairns J, Hijmans RJ. 2009a. Improvement of drought resistance in rice. Adv. Agron. 103:41-99.

Serraj R, Dimayuga G, Gowda V, Guan Y, Hong H, Impa S, Liu DC, Mabesa C, Sellamuthu R, Torres R. 2009b. Drought-resistant rice: physiological framework for an integrated research strategy. In: Serraj R, Benneth J, Hardy B, editors. Drought frontiers in rice: crop improvement for increased rainfed production. Singapore: World Scientific Publishing Co., DOI: 10.1142/9789814280013_0009. p 139-170.

Singh RK, Gregorio GB, Ismail AM. 2008. Breeding rice varieties with tolerance to salt stress. J. Ind. Soc. Coastal Agric. Res. 26:16-21.

Singh S, Mackill DJ, Ismail AM. 2011. Tolerance of longer-term partial stagnant flooding is independent of the *SUB1* locus in rice. Field Crops Res. 121:311-323.

Tao F, Yokozawa M, Zhang Z, Hayashi Y, Grassl H, Fu C. 2004. Variability in climatology ang agricultural production with the East Asia summer monsoon and El Niño South Oscillation. Clim. Res. 28:23-30.

Thomson MJ, de Ocampo M, Egdane J, Rahman MA, Sajise AG, Adorada DL, Tumimbang-Raiz E, Blumwald E, Seraj ZI, Singh RK, Gregorio GB, Ismail AM. 2010. Characterizing the *Saltol* quantitative trait locus for salinity tolerance in rice. Rice 3:148-160.

Tonini A, Cabrera E. 2011. Opportunities for global rice research in a changing world. Technical Bulletin No. 15. Los Baños (Philippines): International Rice Research Institute (IRRI).

Vaghefi N, Nasir Samsudin M, Makmom A, Bagheri M. 2001. The economic impact of climate change on the rice production in Malaysia. Int. J. Agric. Res. 6(1):67-74. Online: http://scialert.net/fulltext/?doi=ijar.2011.67.74&org=10, accessed on 3 Jan. 2012.

Venuprasad R, Sta Cruz M, Amante M, Magbanua R, Kumar A, Atlin G. 2008. Response to two cycles of divergent selection for grain yield under drought stress in four rice breeding populations. Field Crops Res. 107:232-244.

Vergara BS, Mazaredo A. 1975. Screening for resistance to submergence under greenhouse conditions. In: Proceeding of the International Seminar on Deepwater Rice, Bangladesh Rice Research Institute, Dhaka. p 67-70.

Wassmann R, Jagadish SVK, Sumfleth K, Pathak H, Howell G, Ismail A, Serraj R, Redoña E, Singh RK, Heuer S. 2009. Regional vulnerability of rice production in Asia to climate change impacts and scope for adaptation. Adv. Agron. 102:91-133.

Wassmann R, Hien NX, Hoanh CT, Tuong TP. 2004. Sea level rise affecting Vietnamese Mekong Delta: water elevation in flood season and implications for rice production. Clim. Change 66:89-107.

Wassmann R, Dobermann A. 2007. Climate change adoption through rice production in regions with high poverty levels. ICRISAT and CGIAR 35th Anniversary Symposium on Climate-Proofing Innovation for Poverty Reduction and Food Security 22-24 November 2007. SAT eJournal, 4(1):1-24. Online: http://ejournal.icrisat.org/SpecialProject/sp8.pdf, accessed on 1 Jan. 2012.

Weerakoon WMW, Maruyama A, Ohba K. 2008. Impact of humidity on temperature-induced grain sterility in rice (*Oryza sativa* L.). J. Agron. Crop Sci. 194:135-140.

Welch JR, Vincent JR, Auffhammer M, Moyae P. F, Dobermann A, Dawe D. 2010. Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. Proc. Natl. Acad. Sci. USA doi/10.1073/pnas.1001222107.

Widawsky D, O'Toole JC. 1990. Prioritizing the rice biotechnology research agenda for Eastern India. New York (USA): Rockefeller Foundation.

Xia MY, Qi HX. 2004. Effects of high temperature on the seed setting percent of hybrid rice bred with four male sterile lines. Hubei Agric. Sci. 2:21-22.

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

Yang HC, Huang ZQ, Jiang ZY, Wang XW. 2004. High temperature damage and its protective technologies of early and middle season rice in Anhui province. J. Anhui Agric. Sci. 32(1):3-4.

Zeigler RS, Barclay A. 2008. The relevance of rice. Rice 1(1):3-10.

Zou J, Liu AL, Chen XB, Zhou XY, Gao GF, Wang WF, Zhang XW. 2009. Expression analysis of nine rice heat shock protein genes under abiotic stresses and ABA treatment. J. Plant Physiol. 166(8):851-861.