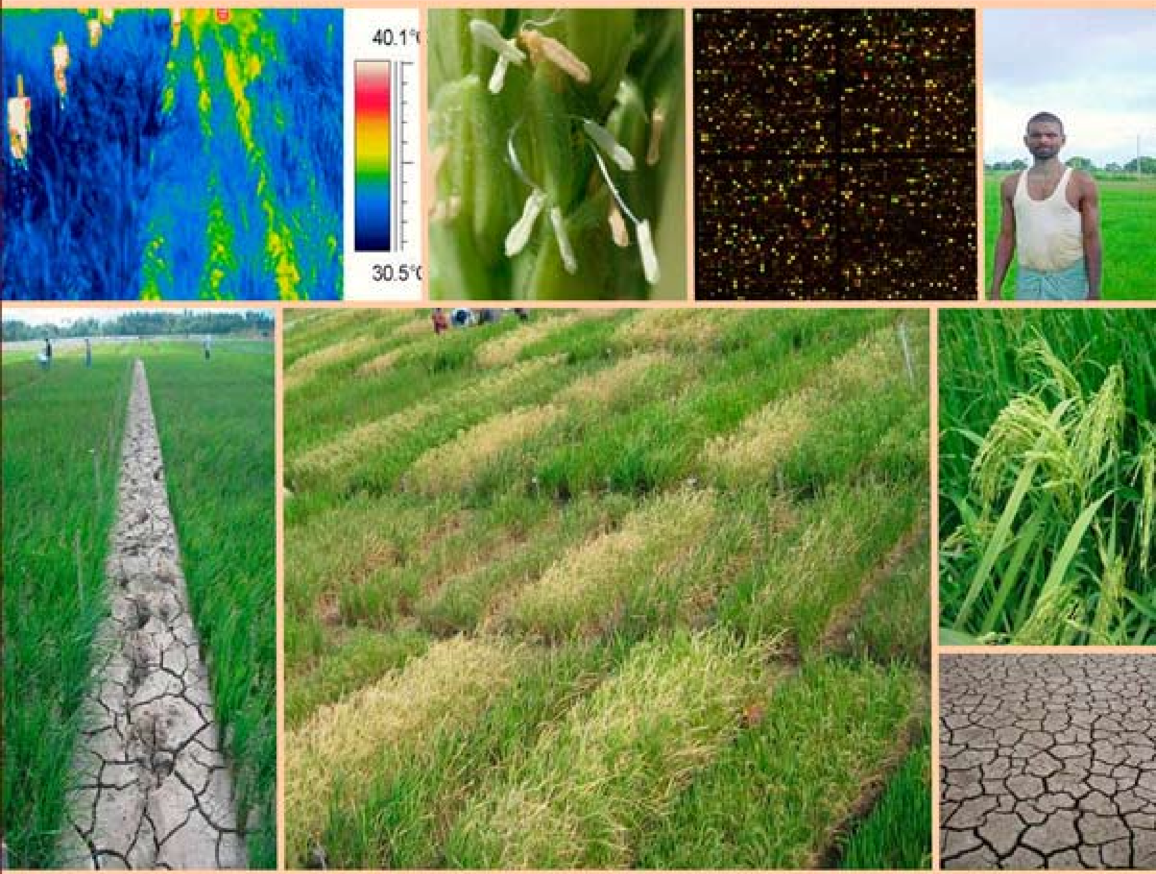
Drought Frontiers in Rice: Crop Improvement for Increased Rainfed Production



Edited by R. Serraj, J. Bennett, and B. Hardy

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Mailing address: IRRI, DAPO Box 7777, Metro Manila, Philippines
Phone: +63 (2) 580-5600
Fax: +63 (2) 580-5699
Email: irri@cgiar.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

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Foreword

Most regions with extensive poverty in Asia are dominated by rainfed ecologies where rice is the principal source of staple food, employment, and income for the rural population. Success has been limited in increasing productivity in rainfed rice systems. Poor people in these ecosystems lack the capacity to acquire food, even at lower prices, because of low productivity in food production and limited employment opportunities elsewhere. Among all abiotic stresses, drought is the major constraint to rice production in rainfed areas across Asia and sub-Saharan Africa. At least 23 million hectares (20% of rice area) are potentially affected in Asia alone. Frequent droughts result in enormous economic losses and have long-term destabilizing socioeconomic effects on resource-poor farmers and communities.

In the context of current and predicted water scarcity scenarios, irrigation is generally not a viable option to alleviate drought problems in rainfed rice-growing systems. It is therefore critical that genetic management strategies for drought focus on maximum extraction of available soil moisture and its efficient use in crop establishment, growth, and maximum biomass and seed yield. However, success has been limited in drought-prone rainfed systems. The rice yields in these ecosystems remain low at 1.0 to 2.5 t ha^{-1}, and tend to be unstable due to erratic and unpredictable rainfall. Drought mitigation, through improved drought-resistant rice varieties and complementary management practices, represents an important exit pathway from poverty.

Recent advances in drought genetics and physiology, together with progress in cereal functional genomics, have set the stage for an initiative focusing on the genetic enhancement of drought resistance in rice. Extensive genetic variation for drought resistance exists in rice germplasm. However, the current challenge is to decipher the complexities of drought resistance in rice and exploit all available genetic resources to produce rice varieties combining drought adaptation with high yield potential, good quality, and tolerance of biotic stresses. The aim is to develop a pipeline for elite "prebred" varieties or hybrids in which drought-resistance genes can be effectively delivered to rice farmers.

The Frontier Project on Drought-Resistant Rice will scale up gene detection and delivery for use in marker-aided breeding. The development of high-throughput, high-precision phenotyping systems will allow genes for component traits to be efficiently mapped, and their effects assessed on a range of drought-related traits, moving the most promising genes into widely-grown rice mega-varieties. To that end, IRRI will establish a drought consortium involving top scientists from both national agricultural research and extension systems and advanced research institutes, and will develop partnerships with extension services and the private sector for the development and evaluation of drought-resistant rice.

IRRI was pleased to convene a planning workshop for the Drought Frontier Project, bringing together some of the most eminent scientists from around the world, to discuss and devise an appropriate research agenda for this project, and to establish the partnership mechanisms for its implementation. The objectives of this workshop were to (1) assess the current status and future challenges facing rice cultivation in drought-prone environments; (2) review the recent progress, breakthroughs, and potential impact of drought research in rice and other tropical crops; (3) identify priority research areas and state-of-the-art methodologies and approaches to tackle drought challenges; and (4) establish a research consortium and an integrated research strategy on drought resistance in rice.

Robert S. Zeigler
Director General
IRRI

Rice drought-prone environments and coping strategies

Drought: economic costs and research implications[1]

Sushil Pandey and Humnath Bhandari

Drought is a major constraint to rice production in Asia. Drought occurs frequently and is one of the major reasons for wide fluctuations in rainfed production. The economic cost of drought estimated in this study was found to be substantial in rainfed areas of eastern India. The economic cost of drought depends largely on the frequency and coverage of drought, and the importance of rice in total farm income. Farmers deploy various coping strategies but these strategies were found to be largely unable to prevent a reduction in income and consumption in rainfed areas of eastern India. As a result, a large number of people fall back into poverty during drought years. The overall implications of these results for research, technology design, and policy interventions for a long-term mitigation of drought are discussed.

Drought is a recurrent phenomenon and an important constraint to rainfed rice production in Asia. Frequent major shortfalls in rice production—the staple crop of Asia—in this vast drought-prone area threaten food security, human health, and livelihood of millions of poor. At least 23 million ha of rice area (20% of the total rice area) in Asia are subject to drought of different intensities (Table 1). Drought is one of the major factors contributing to low and unstable rice production in the region (Fig. 1).

Drought can cause great harm in terms of human suffering, economic loss, and adverse environmental impact. The effect of drought in terms of production losses and consequent human misery is well publicized during years of crop failure. However, losses to drought of milder intensity, although not so visible, can also be substantial. Agricultural production losses, which are often used as a measure of the impact of drought, are only a part of the overall socioeconomic impact. Severe droughts can result in starvation and even death of the affected population. However, different types of economic impact such as production shortfall, price rise, employment and income fall, food insecurity, poor health, and so on arise before such severe consequences

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[1] This paper draws heavily from the book *Economic costs of drought and rice farmers' coping mechanisms* edited by S. Pandey, H. Bhandari, and B. Hardy (2007).

Table 1. Drought-prone rice area in Asia (million ha).

Country	Rice area[a]		Drought-prone rice area	
	UR	RL	UR[b]	RL[c]
India	6.3	16	6.3	7.30
Bangladesh	0.9	6	0.9	0.80
Sri Lanka	0.06	0.2	–	na
Nepal	0.1	1.0	0.1	0.27
Myanmar	0.3	2.5	0.3	0.28
Thailand	0.05	8	–	3.1
Laos	0.2	0.4	0.2	0.09
Cambodia	–	1.7	–	0.20
Vietnam	0.5	3	0.5	0.30
Indonesia	1.1	4	1.1	0.14
China	0.6	2	0.6	0.50
Philippines	0.07	1.2	–	0.24
Total	10	46	10	13

[a]Source: IRRI (1997). [b]Assuming all upland rice (UR) area as drought-prone. [c]Source: Mackill et al (1996). Rainfed lowland (RL) rice area is classified as drought-prone and drought- and submergence-prone. The numbers represented in the table provide lower-bound estimates as the drought-prone and submergence-prone areas are excluded. na = not available.

occur. Because of market failures, farmers attempt to "self-insure" by making costly adjustments in their production practices and adopting conservative practices to reduce the negative impact during drought years. Although these adjustments reduce direct production losses, they do entail some economic costs in terms of opportunities for income gains lost during good years.

In rural areas where agricultural production is a major source of income and employment, a decrease in agricultural production will set off second-round effects through forward and backward linkages of agriculture with other sectors. A decrease in agricultural income will reduce the demand for products of the agro-processing industries that cater to local markets. This will lead to a reduction in income and employment in this sector. Similarly, the income of rural households engaged in providing agricultural inputs will also decrease. This reduction in household income will set off further "knock-on" effects. By the time these effects have been fully played out, the overall economic loss from drought may turn out to be several times more than what is indicated by the loss in production of agricultural output alone. The loss in household income can result in a loss in consumption of the poor, whose consumption levels are already low. Farmers may attempt to cope with this loss by liquidating productive assets, pulling children out of school, migrating to distant places in search

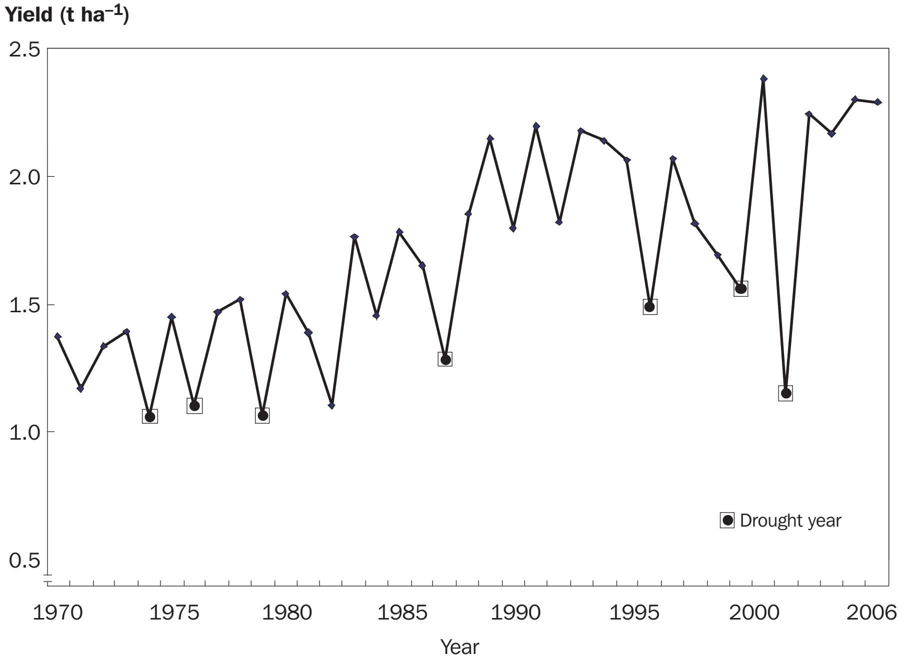

Fig. 1. Trends in rice yield and major drought years, eastern India (Orissa), 1970-2006.

of employment, and going deeper into debt. The economic and social impact of all these consequences can indeed be enormous.

This paper synthesizes the major findings of a recent cross-country comparative study of the impact of drought and farmers' coping mechanisms (see Pandey et al 2007). The countries included in the study were China, India, and Thailand. These countries vary in climatic conditions, level of economic development, rice yields, and institutional and policy contexts of rice farming. The specific regions selected for the study were southern China, eastern India, and northeastern Thailand.

Drought: definition, coping strategies, and consequences[2]

Conceptually, drought is considered to describe a situation of limited rainfall that is substantially below what has been established to be a "normal" value for the area concerned, leading to adverse consequences on human welfare. Although drought is a climatically induced phenomenon, its impact depends on the social and economic context as well. Hence, in addition to climate, economic and social parameters should also be taken into account in defining drought. This makes developing a universally

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[2] Details of different types of drought and farmers' coping mechanisms are presented in Pandey et al (2007).

applicable definition of drought impractical. Three generally used definitions of drought are based on meteorological, hydrological, and agricultural perspectives (Wilhite and Glantz 1985).

Risk-coping strategies can be classified into ex ante and ex post depending upon whether they help to reduce risk or reduce the impact of risk after a production shortfall has occurred. Because of a lack of efficient market-based mechanisms for diffusing risk, farmers modify their production practices to provide "self-insurance" so that the likely impact of adverse consequences is reduced to an acceptable level. These ex ante strategies help reduce fluctuations in income and are also referred to as income-smoothing strategies. These strategies can, however, be costly in terms of forgone opportunities for income gains as farmers select safer but low-return activities.

Ex ante strategies can be grouped into two categories: those that reduce risk by diversification and those that do so by imparting greater flexibility in decision making. Diversification is simply captured in the principle of not putting "all eggs in one basket." The risk of income shortfall is reduced by growing several crops that have negatively or weakly correlated returns. This principle is used in different types of diversification common in rural societies. Examples include spatial diversification of farms, diversification of agricultural enterprises, and diversification from farm to nonfarm activities.

Maintaining flexibility is an adaptive strategy that allows farmers to switch between activities as the situation demands. Flexibility in decision making permits farmers not only to reduce the chances of low income but also to capture income-increasing opportunities when they do arise. Examples are using split doses of fertilizers, temporally adjusting input use to crop conditions, and adjusting the area allocated to a crop depending on the climatic conditions. Although postponing agricultural decisions until uncertainties are reduced can help lower potential losses, such a strategy can also be costly in terms of income forgone if operations are delayed beyond the optimal biological window. Other ex ante strategies include maintaining stocks of food, fodder, and cash.

Ex post strategies are designed to prevent a shortfall in consumption when the income drops below what is necessary for maintaining consumption at its normal level. Ex post strategies are also referred to as consumption-smoothing strategies as they help reduce fluctuations in consumption. These include migration, consumption loans, asset liquidation, and charity. A consumption shortfall can occur despite these ex post strategies if the drop in income is substantial.

Farmers who are exposed to risk use these strategies in different combinations. Over a long period of time, some of these strategies are incorporated into the nature of the farming system and are often not easily identifiable as risk-coping mechanisms. Others are deployed only under certain risky situations and are easier to identify as responses to risk.

Opportunity costs associated with the deployment of various coping mechanisms can, however, be large. Climatic uncertainties often compel farmers, particularly those who are more risk-averse, to employ conservative risk management strategies that reduce the negative impact in poor years, but often at the expense of reducing the average productivity and profitability. For example, by growing drought-hardy but low-yielding traditional rice varieties, farmers may be able to minimize the drought risk but may end up sacrificing a potentially higher income in normal years. Also, poor farmers in high drought-risk environments may be reluctant to invest in seed-fertilizer technologies that could increase profitability in normal years but lead to a loss of capital investment in poor years. In addition to these opportunity costs, poor households that are compelled to sell their productive assets such as bullocks and farm implements will suffer future productivity losses as it can take them several years to reacquire those assets. A cut in medical expenses and children's education will affect future income-earning capacity of the household. Such an impact may linger on into the future generation also. The loss of income and assets can convert transient poverty into chronic poverty, making the possibility of escape from poverty more remote (Morduch 1994, Barrett 2005).

Frequency of drought and economic loss[3]

An analysis of historical rainfall data indicated that drought is a regular phenomenon in all three regions (eastern India, northeastern Thailand, and southern China). The probability of drought varies in the range of 0.1–0.4, with the probability being higher in eastern India than in southern China and northeast Thailand (Fig. 2). The probability of late-season drought was found to be higher than that of early-season drought generally. Late-season drought was also found to be spatially more covariate than early-season drought. This means that late-season drought tends to cover large areas. As rice yield is more sensitive to drought during flowering/grain-filling stages (i.e., during the late season, according to the definition used here), late-season drought is thus likely to have a larger aggregate production impact than early-season drought.

The temporal instability in rice production as measured by the de-trended coefficient of variation of rice yield was found to be high in eastern India (17%) relative to southern China (4%) and northeast Thailand (9%). The corresponding much lower coefficients of variation for southern China and northeast Thailand indicated that droughts in these regions are not as covariate spatially as in eastern India, with their effects being limited to some pockets. Given the nature of the temporal variability, the aggregate impact of drought on production is also likely to be higher in eastern India than in the other two regions.

The estimated average loss in rice production during drought years for eastern India is 5.4 million tons (Table 2). This is much higher than for northeast Thailand (less than 1 million tons) and southern China (around 1 million tons but not statistically significant). The loss (including any nonrice crops included) during drought years is thus 36% of the average value of production in eastern India. This indeed represents a massive loss during drought years (estimated at US$856 million).

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[3] Estimation methods for various empirical results presented are described in Pandey et al (2007).

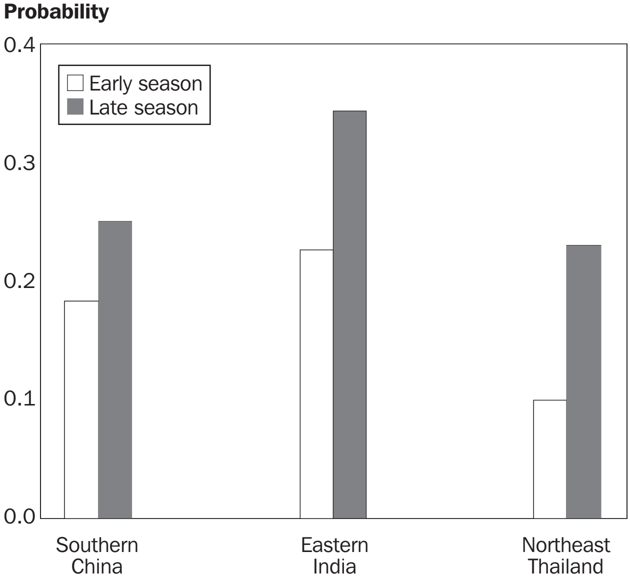

Fig. 2. Estimated probability of early- and late-season drought in southern China (1982-2001), eastern India (1970-2000), and northeast Thailand (1970-2002).

Table 2. Estimated value of crop production losses due to drought using rainfall-based drought years, 1970-2002.

Country[a]	Drought years			Annual	
	Quantity of rice production loss (million t)	Value of crop production loss[b] (million $)	Ratio of loss to average value of production (%)	Value of crop production loss[b] (million $)	Ratio of loss to average value of production (%)
Southern China	1.2	133	3	16	0.4
Eastern India	5.4	856 ***	36	162	7.0
Northeast Thailand	0.7	85 *	10	10	1.2

[a] The values are estimated based on secondary data of study provinces/states. [b] The value of production losses is estimated using both rice and nonrice crops for India while only the rice crop is used for China and Thailand. * = $P < 0.1$ and *** = $P < 0.01$.

Table 3. Percentage change in rice area, yield, and production among sample farm households in drought years compared with normal years.

Rice	Southern China	Eastern India	Northeast Thailand
Area	–19	–36	–21
Yield	–31	–54	–45
Production	–44	–71	–56

As droughts do not occur every year, the above estimate of production loss needs to be averaged over a run of drought and nondrought years to get the annual average loss estimate. Again for eastern India, this represents an annual average loss of $162 million (or 7.0% of the average value of output). For northeast Thailand and southern China, the losses were found to be much smaller and averaged less than $20 million per year (or less than 1.5% of the value of output).

The estimates thus indicate that, at the aggregate level, the production losses are much higher for eastern India than for the other two regions. Lower probability of drought, a smaller magnitude of loss during drought years, and less covariate nature of drought together have reduced production losses at the aggregate level in the other two regions relative to eastern India.

The overall economic cost of drought includes the value of production losses, the costs farmers incur in making adjustments in production systems during drought years, opportunities for gains forgone during good years by adopting ex ante coping strategies that reduce losses during drought years, the generally lower productivity of drought-prone areas due to moisture deficiency, and the costs of government programs aimed at long-term drought mitigation. The average annual cost for eastern India is in the neighborhood of $400 million (Pandey et al 2007). Overall, the cost of drought is a substantial proportion of the agricultural value added in eastern India.

Household-level consequences of drought

A detailed analysis of the household-level impact of drought was conducted using farm survey data. Drought-affected households suffered rice production losses of 44–71% (Table 3). Even in southern China and northeast Thailand, where aggregate production losses were small, production losses for the households affected by drought were substantial. Production losses resulted from both yield loss and area loss. The loss in yield, however, accounted for the major share of production losses. Across the toposequence, production losses were higher in upper fields that drain quickly than in bottom lands, which tend to have more favorable hydrological conditions.

Drought resulted in an overall income loss of 24% to 58%.[4] The drop in rice income was the main factor contributing to the total income loss. Earnings from farm labor also dropped substantially because of reduced labor demand. Farmers attempted to reduce loss in agricultural income during drought years by seeking additional employment in the nonfarm sector. This mainly included employment as wage labor in the construction sector, for which farmers often migrated to distant places. The additional earnings from nonfarm employment were clearly inadequate, however, to compensate for the loss in agricultural income.

Farmers relied on three main mechanisms to recoup this loss in total income: the sale of livestock, sale of other assets, and borrowing. These adjustment mechanisms helped recover only 6–13% of the loss in total income. Compared with normal years, households still ended up with a substantially lower level of income despite all these adjustments. Thus, all the different coping mechanisms farmers deployed were found to be inadequate to prevent a shortfall in income during drought years.

The incidence of poverty increased substantially during drought years. Almost 13 million additional people "fell back" into poverty as a result of drought (Fig. 3). This is a substantial increase in the incidence of poverty and translates into an increase in rural poverty at the national level by 1.8 percentage points. Some of the increase in poverty may be transitory, with households being able to climb out of poverty on their own. However, other households whose income and assets fall below certain threshold levels may end up joining the ranks of the chronically poor (Barrett 2005). The data collected, however, did not permit the estimation of the proportion of these two categories of households. Households with small farm sizes, with proportionately more area under drought-prone upland fields, and with a smaller number of economically active members, are more vulnerable to such adverse income consequences of drought.

In terms of crop management practices, farmers seem to have less flexibility in making management adjustments in rice cropping in relation to drought. Other than delaying crop establishment if the rains are late, replanting and resowing when suitable opportunities arise, and some reduction in fertilizer use, farmers mostly follow a standard set of practices irrespective of the occurrence of drought. This could partly be because drought mostly occurs during the late season, by which time opportunities for crop management adjustments to reduce losses are no longer available. The timing of drought (mostly late rather than early) and the lack of suitable technological options probably has limited flexibility in making tactical adjustments in crop management practices to reduce losses.

Since rice is the staple food, a loss in its production can be expected to result in major adjustments in consumption. Such adjustments could involve a reduced sale of rice, reduced quantity retained as seeds for the following year, increased amounts purchased, substitution of other crops for rice, supplementation of food deficit by other

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[4] The household-level impact of drought presented here is based mainly on the study in eastern India. Relative to eastern India, impact in northeast Thailand and southern China was found to be quite small and, hence, is not discussed here.

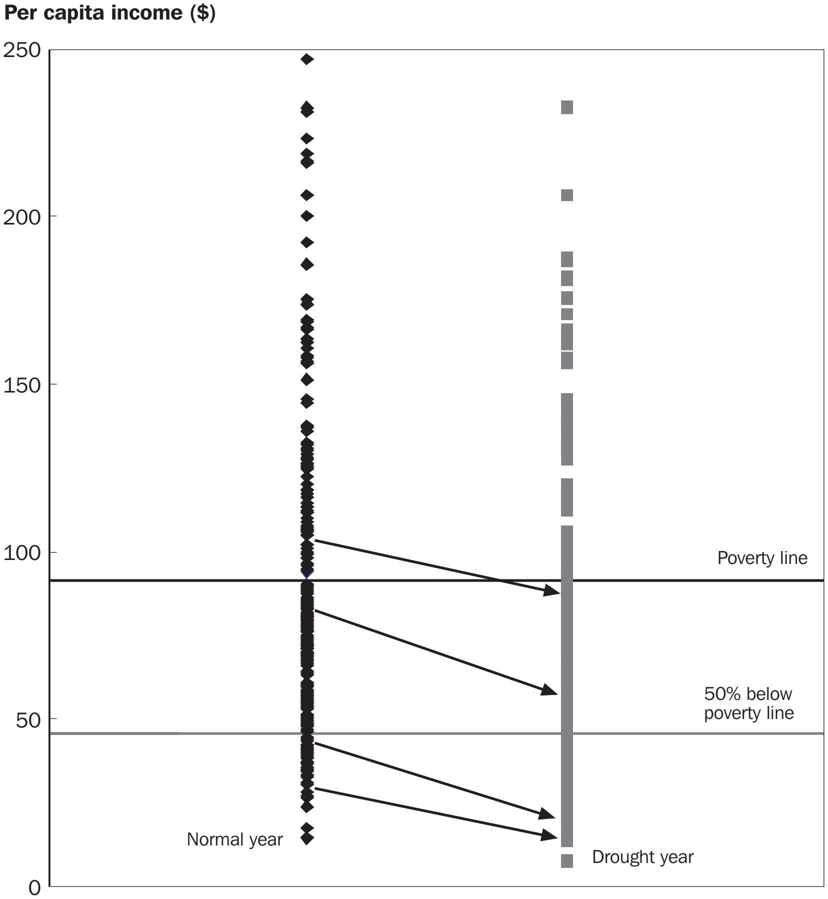

Fig. 3. Effect of drought on incidence and severity of poverty, Jharkhand, India (each dot refers to a household).

types of food not normally consumed, and, in the worst-case scenario, a reduction in consumption.

Farmers made all these types of adjustments to a varying degree. Despite these various adjustments, most farmers were unable to maintain consumption at the pre-drought level. They reduced both the number of meals eaten per day and the quantity consumed per meal. As a result, the average number of meals eaten per day dropped from close to three to close to two, with 10–30% of the households reducing their frequency of food intake to one meal per day. A large proportion (60–70%) of the households also reduced the quantity of food consumed per meal. In addition, households consumed other "inferior" food items that were not normally consumed.

The interruption and/or discontinuation of children's education is a disinvestment in human capital, which will most definitely reduce their future earning potential in most cases. An important pathway for escape from poverty may be foreclosed as a result of drought. More than 50% of the farmers reported curtailing children's education.

Relative to eastern India, the economic costs in southern China and northeast Thailand were found to be small, in both absolute and relative terms. Production losses at the aggregate level in these two regions were relatively small because of a lower frequency and less covariate nature of drought. In addition, rice accounted for a smaller proportion of household income because of a more diversified income structure. The differences in rice production systems, the level of income diversification, and the nature of drought in these latter two regions are hence the major factors determining the relative magnitudes of economic losses.

Implications

Agricultural research

Improved rice technologies that help reduce losses to drought can play an important role in long-term drought mitigation. Important scientific progress is being made in understanding the physiological mechanisms that impart tolerance of drought (Blum 2005, Lafitte et al 2006). Similarly, progress is being made in developing drought-tolerant rice germplasm through conventional breeding and the use of molecular tools (Bennett 1995, Atlin et al 2006, Serraj 2005). The probability of success in developing rice germplasm that is tolerant of drought is likely to be substantially higher now than what it was a decade ago. Complementary crop management research to manipulate crop establishment, fertilization, and general crop care for avoiding drought stress, better use of available soil moisture, and enhancing the plant's ability to recover rapidly from drought can similarly help reduce losses.

Despite the potential role of improved technologies in drought mitigation, the level of agricultural research in developing countries is generally low. Although industrialized countries invest about 2.6% of their agricultural GDP in research, the research intensity (or the ratio of research expenditure to agricultural GDP) for developing countries has been estimated to be around 0.62% (Pal and Byerlee 2003). For China and India, research intensities are only 0.43% and 0.29%, respectively. Clearly, agricultural research in the developing countries of Asia remains underinvested. The total agricultural research investment in India in 1998-99 was about $430 million (Pal and Byerlee 2003). The economic losses from drought alone as estimated in this study by considering just rainfed rice-growing areas are close to this figure.

The allocation of research resources to rainfed areas and specifically to address abiotic constraints such as drought and submergence is even lower relative to the size of losses resulting from these constraints. A recent study from India illustrates the case in point. It has been found that the allocation of rice research resources to rainfed areas in India is disproportionately small relative to the potential contribution of these areas in making efficiency and equity impacts (Pandey and Pal 2007). The share of even this limited amount of resources targeted to address abiotic constraints such as drought and submergence is less than 10%.

It has been established that the marginal productivity of research resources may now be higher in rainfed environments than in irrigated environments and that agricultural research in unfavorable (rainfed) environments can generate a substantial poverty impact (Fan et al 2005). There is a strong justification for increasing research intensity in agriculture and allocating a larger proportionate share to rainfed areas to address drought and submergence, which are the dominant constraints to productivity growth.

Technology design considerations

Several design features need to be considered when developing improved technologies for effective drought mitigation. An important design criterion is that the technologies should improve flexibility in the decision regarding crop choices, the timing and method of crop establishment, and the timing and quantity of various inputs to be used. Flexibility in agricultural technologies permits farmers not only to reduce the chances of low income but also to adaptively capture income-increasing opportunities when they do arise. Technologies that lock farmers into a fixed set of practices and timetables do not permit effective management of risk in agriculture. In fact, the empirical analyses presented in this report indicate that farmers do not seem to have much flexibility in making management adjustments in rice cropping in relation to drought. Other than delaying crop establishment if rains are late, replanting and resowing when suitable opportunities arise, and some reduction in fertilizer use, farmers mostly follow a standard set of practices irrespective of the occurrence of drought. The timing of drought (mostly late rather than early) and the lack of suitable technological options have probably limited flexibility in making tactical adjustments in crop management practices to reduce losses. Examples of technologies that provide greater flexibility are varieties that are not adversely affected by delayed transplanting caused by early-season drought, varieties that perform equally well under both direct seeding and transplanting, and crop management practices that can be implemented over a wider time window.

Losses in agricultural production and income are important factors that contribute to increases in poverty during drought years. Technologies that reduce yield losses during drought years can avoid such adverse impacts on poverty even if there may be some associated trade-offs in yield during favorable years. Hence, in terms of poverty impact, higher priority should be accorded to research focused on lopping off the lower tail of the yield distribution than to raising average yield by improving performance during normal years, if there are trade-offs involved in achieving both simultaneously.

Late-season drought is more frequent and tends to have more serious economic consequences for poor farmers than early-season drought. In addition to having to deal with the consequences of low or no harvest, farmers also lose their investments in seed, fertilizer, and labor if the crop is damaged by late-season drought. Although early-season drought may prevent planting completely, farmers can switch early to other coping strategies such as wage labor and migration to reduce income losses in such years. Thus, the poverty impact of technology is likely to be higher if research focuses on late-season drought if tolerance of early- and late-season drought cannot be achieved simultaneously.

In rainfed areas, the land endowment of farmers typically consists of fields across the toposequence that have different hydrological conditions. Fields in the upper part of the toposequence are typically more drought-prone than those in the lower part. Farmers use such a hydrologically diversified portfolio of land by growing different varieties of rice that match field hydrological features. In addition, farmers grow a range of varieties for other reasons such as staggering of labor demand, grain quality, taste, and suitability to various uses. Breeding programs that produce a wider choice of plant materials with different characteristics and varying responses to drought that correspond with field hydrological features can play an important role in effective protection from drought.

Crop diversification is an important drought-coping mechanism of farmers. Rice technologies that promote but do not constrain such diversification are therefore needed. In rainfed areas, shorter-duration rice varieties can facilitate planting of a second crop using residual moisture. Similarly, rice technologies that increase not just yield but also labor productivity will facilitate crop and income diversification. Higher labor productivity in rice production will help relax any labor constraint to diversification that may exist. Examples of such technologies are selective mechanization, direct seeding, and chemical weed control.

Complementary options

The development of water resources is an important area that is emphasized in all three countries for providing protection against drought. Opportunities for large-scale development of irrigation schemes that were the hallmark of the Green Revolution are limited now because of high costs and increasing environmental concerns (Rosegrant et al 2002). However, there are still substantial opportunities to provide some protection from drought through small and minor irrigation schemes and through land-use approaches that generally enhance soil moisture and water retention (Shah 2001, Moench 2002). Similarly, watershed-based approaches that are implemented in drought-prone areas of India provide opportunities for achieving long-term drought proofing by improving overall moisture retention within the watersheds (Rao 2000).

In all three countries studied, a major response to drought has been to provide relief to the affected population. Although the provision of relief is essential to reduce the incidence of hunger and starvation, the major problems with relief programs are slow response, poor targeting of beneficiaries, and limited coverage due to budgetary constraints. A “fire-fighting” approach that underlies the provision of drought relief cannot provide long-term drought proofing despite the large amount spent during drought years (Rao 2000, Hirway 2001). It is important that the provision of relief during drought years be complemented by a long-term strategy of investing in soil and water conservation and use, policy support, and infrastructure development to promote crop and income diversification in drought-prone areas (Rao 2000).

The scientific advances in meteorology and informatics have made it possible now to forecast drought with reasonable degrees of accuracy and reliability. Various indicators such as the Southern Oscillation Index (SOI) are now routinely used in several countries to make drought forecasts (Wilhite et al 2000, Meinke and Stone 2005). Suitable refinements and adaptations of these forecasting systems are needed to enhance drought preparedness at the national level as well as to assist farmers in making more efficient decisions regarding the choice of crops and cropping practices (Abedullah and Pandey 1998). Improvements in drought forecasting systems, the identification of efficient agricultural management practices to reduce the impact of drought, and the provision of timely advice to farmers are activities that can help reduce the overall economic costs of drought and improve preparedness to manage drought risk effectively.

Although technological interventions can be critical in some cases, this is not the only option for improving the management of drought. A whole gamut of policy interventions can improve farmers' capacity to manage drought through more effective income- and consumption-smoothing mechanisms. Improvements in rural infrastructure and marketing that allow farmers to diversify their income sources can play an important role in reducing overall income risk. Investment in rural education can similarly help diversify income. In addition, such investments contribute directly to income growth that will further increase farmers' capacity to cope with various forms of agricultural risks. Widening and deepening of rural financial markets will also be a critical factor for reducing fluctuations in both income and consumption over time (Barrett 2005). Although the conventional forms of crop insurance are unlikely to be successful because of problems such as moral hazard and adverse selection (Hazell et al 1986), innovative approaches such as rainfall derivatives and international re-insurance of agricultural risks can provide promising opportunities (Skees et al 2001, Glauber 2004). However, these alternative schemes have not yet been adequately evaluated. More work is needed for developing and pilot testing new types of insurance products and schemes suited to hundreds of millions of small farmers of Asia who grow rice primarily for subsistence.

Concluding remarks

The socioeconomic impacts of drought are enormous even in subhumid rice-growing areas. Drought causes huge economic costs, in terms of both actual economic losses during drought years and losses arising from the opportunities for economic gains forgone. The provision of relief has been the main form of drought management of the government. Although important in reducing the hunger and hardship of the affected people, the provision of relief alone is clearly inadequate and may even be an inefficient response for achieving longer-term drought mitigation. Given the clear linkage between drought and poverty, it is critically important to include drought mitigation as an integral part of a rural development strategy. Policies that in general increase income growth and encourage income diversification also serve to protect farmers from the adverse consequences of risk, including that of drought.

The scientific progress made in understanding the physiology of drought and in the development of biotechnology tools has opened up promising opportunities for making a significant impact on drought mitigation through improved technology. However, agricultural research in general remains grossly underinvested in the developing countries of Asia. This is a cause for concern, not only for drought mitigation but also for promoting overall agricultural development.

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Notes

Authors' address: International Rice Research Institute, DAPO Box 7777, Metro Manila, Philippines.

Modeling spatial and temporal variation of drought in rice production

Robert J. Hijmans and Rachid Serraj

We present a preliminary crop growth simulation model-based characterization of the spatial and temporal distribution of drought stress in rice production. The main objectives of this approach are to assist in estimating the potential benefits of drought-tolerant rice varieties, and to help select target areas for evaluation and dissemination of these varieties. The simulation model results provide a simple way to reduce daily weather data to a single or a few indices, to be used as predictors in characterization or data-mining modeling methods. We emphasize the need to refine the simulation modeling methods and to integrate the simulation results with census data and those obtained from studies of farmer behavior in response to drought, and the effect of drought on rice yield in farmers' fields.

Rice evolved in semiaquatic environments and is particularly sensitive to drought stress (O'Toole 2004). Drought is typically defined as a rainfall shortage compared with a normal average for a region. However, drought occurrence and effects on rice productivity often depend more on rainfall distribution than on total seasonal rainfall. A typical case is what happened in a recent experiment at IRRI (Los Baños, Philippines) during the wet season of 2006. Seasonal rainfall exceeded 1,200 mm, including a downpour, during a major typhoon (Milenyo), of 320 mm in a single day. Yet, a short dry spell that coincided with the flowering stage of the crop resulted in a dramatic decrease in grain yield and harvest index compared with those of the irrigated control (Serraj et al, unpublished).

An obstacle to the estimation of potential impacts of drought-tolerant varieties is that the effect, and hence adoption and impact, of these technologies is highly site- and time-specific. That is, their utility depends strongly on spatially and temporally variable environmental conditions, particularly rainfall, as well as on social and economic circumstances (Pandey and Bhandari, this volume). In this paper, we discuss only the aspects of environmental variation, aiming at estimating the potential yield benefits of drought-tolerant rice varieties and selecting target areas for evaluation and dissemination.

Defining drought

The meaning of the term "drought" often depends on a disciplinary outlook, and this includes meteorological, hydrological, and agricultural perspectives. Agricultural drought occurs when soil moisture is insufficient to meet crop water requirements, resulting in reduced crop growth and yield losses. Depending on timing, duration, and severity, this can result in catastrophic, chronic, or inherent drought stress, which would require different coping mechanisms, adaptation strategies, and breeding objectives. The 2002 drought in India could be described as typical for a catastrophic event, as it affected 55% of the country's crop area and 300 million people. Rice production was 20% below the trend values (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 impoverishment of the affected population, with dramatic, and often long-term, socioeconomic consequences (Pandey and Bhandari, this volume).

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 2,000 and 2,500 kg ha^{-1}, far below achievable yield potential. 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 there is large uncertainty about the attainable yield (Pandey et al 2007).

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 (Ding et al 2005).

Systems analysis and simulation

Breeding strategies for improved drought tolerance could benefit from detailed and precise characterization of the target population of environments (TPEs). One approach to characterization is the classification of rainfall patterns in relation to crop phenology (e.g., Saleh et al 2000). Although this can be very useful, it is rather difficult to do objectively, particularly for larger areas. An alternative approach involves the use of crop growth simulation models. Crop growth models encapsulate knowledge of eco-physiological processes and allow simulation of crop yield for specific varieties and locations. In this way, complex location data, such as daily weather data, can be summarized with an easy-to-interpret index such as crop yield.

For example, Heinemann et al (2008) recently used a crop simulation model to determine the patterns of drought stress for short- and medium-duration upland rice across 12 locations in Brazil. This study allowed the characterization of drought-prone TPE and confirmed the greater yield impact of drought stress when it occurred around flowering and early grain-filling.

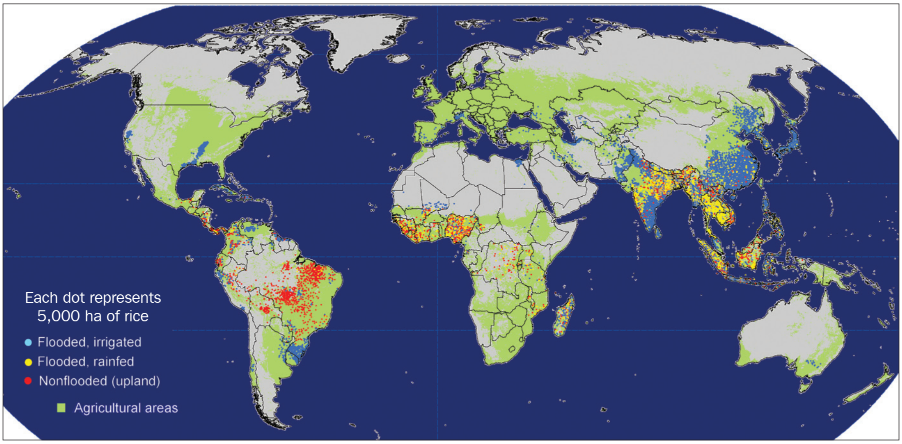

Fig. 1. Global rice area by major rice ecosystems.

Simulation models can also provide a tool to assist in understanding, and incorporating, genotype-by-environment interaction, by combining mechanistic understanding of a drought (Chapman 2008). Given a historical record of weather for a location, the probability of a yield increase (and maybe a decrease) resulting from the incorporation of any trait into the crop can be simulated. Combining the probabilities for yield change with the farmers' adversity to risk gives a strong indication to a breeder of the desirability of incorporating a particular drought trait for cultivars to be grown in a specific location. System analysis can hence allow breeding for specific drought-adaptive traits to be targeted to those geographical regions where their benefit will be largest (Sinclair and Muchow 2001). However, in the case of rice, most simulation efforts have focused on irrigated environments, and an improved rice model needs to be developed or adapted specifically for the drought-prone rainfed systems, based on better physiological understanding of rice interaction with the environment under water deficits.

Distribution of rice production systems and rainfall

Worldwide, there are more than 100 million ha of rice, with 89% in Asia. About 45% of the rice area is rainfed, of which 25% is never flooded (upland). Asia has large areas of rainfed rice in eastern India and Bangladesh, northeast Thailand, Cambodia, and the island of Sumatra in Indonesia (Fig. 1). The majority of rice production in Africa is rainfed (Balasubramanian et al 2007).

It is not a surprise that rainfed rice is not produced much in very dry areas. In Asia, about 11% of irrigated rice is produced in areas with less than 750 mm of average annual rainfall, versus 0.5% of rainfed rice. About 23% of irrigated rice is in areas with less than 1,000 mm of rainfall versus 4% of rainfed rice (Fig. 2). Rainfed rice in very dry areas is either a misclassification or it is planted in atypical humid locations on the landscape, such as valley bottoms and marshes.

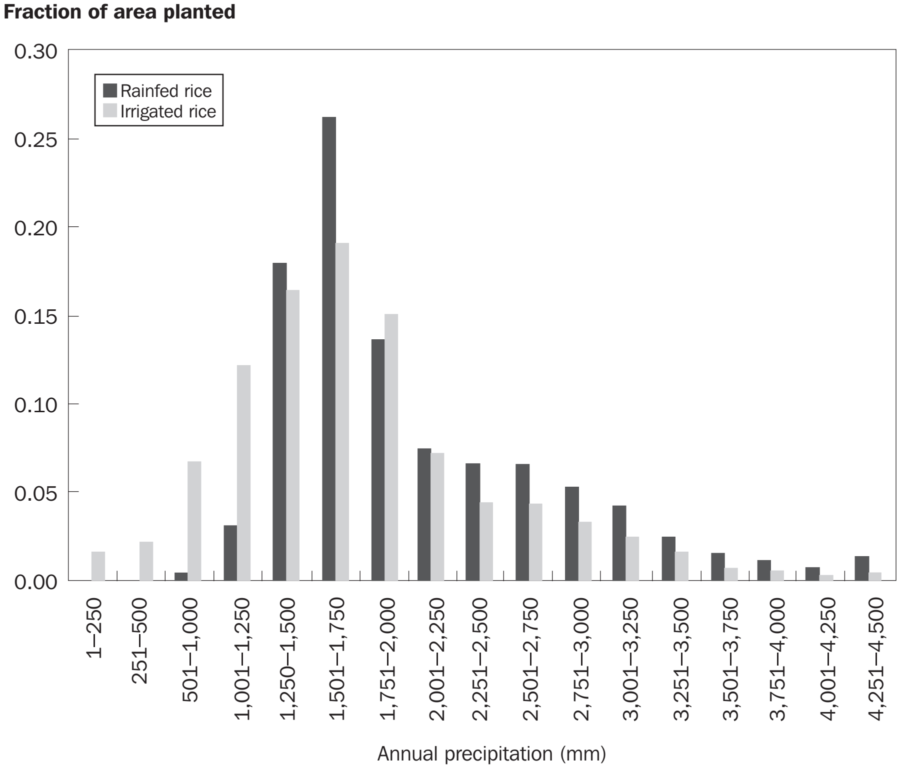

Fig. 2. Distribution of rainfed and irrigated rice area by annual precipitation.

There is also a large amount of irrigated rice in very humid areas. This is in part because irrigation in many cases provides only a part of the water required, if and when necessary, for example, during a dry spell. It is also because irrigation allows for the production of a second or third rice crop in the dry season, and in some of these areas irrigated rice during the rainy season is in most years equivalent to rainfed rice.

Water as a yield-limiting factor

We used the ORYZA2000 model (Bouman et al 2003) calibrated for variety IR72. We ran the model for 1 degree grid cells with 9 years of daily weather data estimated from satellite observations by NASA (data available at http://earth-www.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi). Rainfed rice can be produced on land that never gets flooded (upland rice) or in fields that can get flooded when there is sufficient water and bunds are present (rainfed lowland rice). The source of water in these fields can be local rainfall or water flowing laterally into the fields. Here, we show only results for rainfed lowland rice (flat, bunded fields). A single rainfed crop was considered for each cell. Planting time was estimated by first simulating rainfed rice crops that were planted at 2-week intervals throughout the year. We then selected the fortnight

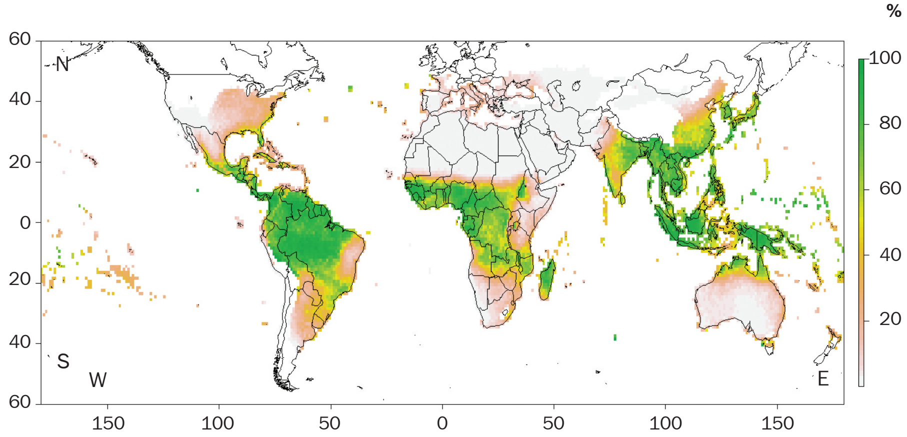

Fig. 3. Simulated rainy-season rice yield of rainfed lowland rice (flat, flooded fields) relative to irrigated conditions (%). Computed with the ORYZA2000 simulation model for variety IR72.

that most frequently (across the 9 years) gave the highest yield. We subsequently used that planting period for all 9 years to compute yields for rainfed and for irrigated conditions.

Figure 3 shows the simulated yield of rainfed lowland rice relative to the simulated yield with full irrigation. We refer to this as the "relative rice yield." We use relative yield because that makes it easier to compare drought effects across sites, as it is not influenced by the potential yield, which depends on temperature and radiation, but only by the (model prediction of) yield limitation due to drought.

Although our simulations do not capture many known sources of variation, such as local hydrological processes and differences in soil types, we believe that the results nevertheless show some basic facts about drought in rainfed rice. First of all, there are some places where you cannot grow much rice without irrigation. This does not necessarily mean that water stress is an important problem there. In fact, some of the most productive irrigated rice areas are found here, including the Punjab in India and the Nile Valley in Egypt. On the other hand, if water becomes scarce in these regions ("inherent drought")—as is happening in many areas—water-saving irrigation technologies and appropriate varieties would be very useful.

Figure 4 shows relative yield as a function of rainfall during the growing season, computed across all grid cells where rice can grow. It shows that, when rainfall is below 450 mm, rice production is virtually impossible. Only at 750–850 mm does the median simulated yield pass 50% of irrigated yield during that season. But, as we have seen (Fig. 4), very few farmers choose to plant rainfed rice under these conditions, probably because it is very risky.

Variation in simulated yield between sites is highest at the intermediate relative yields. When rainfall is very low or very high, the distribution of rainfall in the growing season, or the effect of other climate variables (the atmospheric evaporative

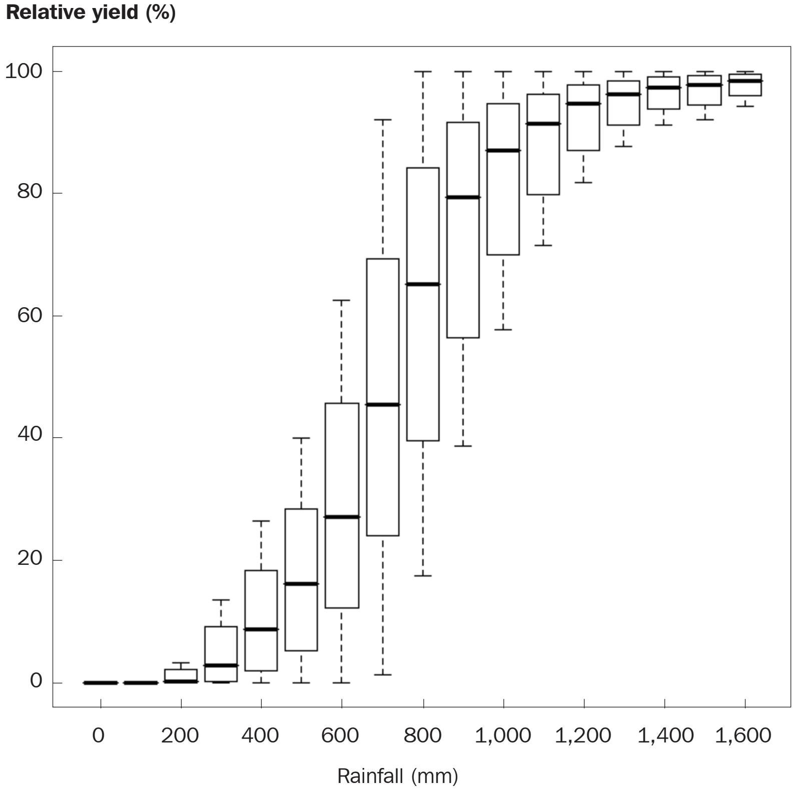

Fig. 4. Simulated rainy-season rice yield of rainfed lowland rice (flat, flooded fields) relative to irrigated conditions (%), by the amount of rain during the growing season. Box and whisker plot showing quartiles and median values. Computed with the ORYZA2000 simulation model for variety IR72.

demand), does not matter much. But, at 600 to 800 mm during the growing season, relative yields range between 0 and 100%.

Figure 4 summarizes variation in relative yield between years, whereas Figure 5 shows variation between years within sites, expressed as the coefficient of variation. Note that, at an average seasonal rainfall of around 1,100 mm, the median coefficient of variation is still rather high at 25%. This appears to be an important property of rainfed rice production: even if the expected (median) yield is good, there can be a high frequency of years with poorer yields. The variation we found is probably a bit exaggerated because we did not allow for adaptive planting times, depending on the onset of rainfall. However, this accounts for only a part of the variation in yield reduction through drought, so even with further refining of our modeling approach, the between-year variation will likely remain high.

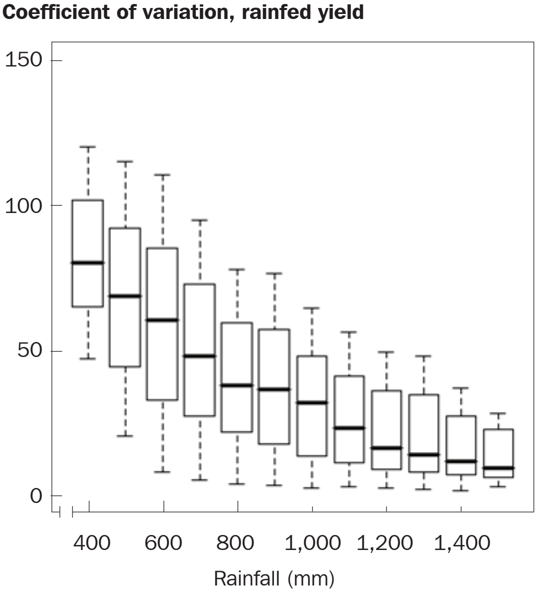

Fig. 5. Simulated coefficient of variation (over 9 years, 1993-2001) of rainy-season rice yield of rainfed lowland rice (flat, flooded fields), by the amount of rain during the growing season. Box and whisker plot showing quartiles and median values. Computed with the ORYZA2000 simulation model for variety IR72.

Drought-tolerant varieties will allow farmers to obtain higher yields without adjusting their cropping practices. However, they could also respond by adjusting cropping practices and shifting rainfed rice production to drier areas or seasons. Shifting rice production out of the main rainy season can be attractive because, if there is no drought stress, yields can often be higher when the dry season is associated with higher solar radiation (fewer clouds) and lower temperatures (longer growing season, fewer respiratory losses). In addition, early planting and harvesting may allow for double cropping of rice. Such shifts appear to be particularly relevant in eastern India, Bangladesh, and Southeast Asia (data not shown). Although drought tolerance alone can probably not do much in this context, particularly as it cannot help in planting in dry fields before the rains start, it could be very useful in combination with irrigation (pumps) to get the crop started, but with minimal additional irrigation to save on water and fuel costs.

The potential benefits of drought tolerance

Current research aims to improve the data used to run the models, and by running models for different rice ecosystems and for different varieties to contrast existing versus new drought-tolerant varieties, and to contrast current cropping practices with water-saving technologies. Simulation models are in principle very useful for estimating the benefit (in terms of yield) of drought tolerance and other traits. This could be achieved by comparing a standard variety with a variety with increased tolerance (e.g., Hijmans et al 2003). However, right now, the ORYZA2000 model has not been calibrated for any of the more drought-tolerant lines that the IRRI breeding program has developed. If the physiological mechanisms that make these new lines more drought tolerant were known, they could be incorporated into a hypothetical variety for simulation.

Because of the current knowledge gaps in understanding drought-tolerance mechanisms (Serraj et al, this volume), we decided to express drought not as a physiological trait (water demand), but rather as an environmental supply in terms of available water. The assumption is that increasing water availability to a standard rice variety is equivalent to some types of drought tolerance. We implemented this by increasing the amount of rain, on each rainy day, by 10%. Although at this point we cannot relate that to existing varieties, it does serve as an indicator of how much and where drought tolerance could be beneficial. Moreover, preliminary research findings at IRRI suggest that an important characteristic of some of our new drought-tolerant varieties is that they are able to extract more water from the soil, on the order of 7% more water (Bernier et al 2008).

Figure 6 shows the results of these simulations. As expected, drought tolerance is not useful in extremely dry or in very wet areas. Areas with rainfall between 550 and 1,050 mm during the growing season would have the most benefits, typically on the order of 500 kg ha^{-1} (on average across years). These are the areas with moderate to high relative yields (Fig. 4). When increasing water availability by 25%, the yield effects generally doubled relative to a 10% increase (data not shown).

Figure 7 shows the yield effects of drought tolerance. It could clearly be very important for large tracts in Africa. We also looked at the benefit of drought tolerance in terms of impact on total production. This was computed by multiplying the yield gain by the area under rainfed rice for each grid cell. Different regions then come out as most important (Fig. 8). Drought tolerance could be particularly important to boost production in eastern India and Thailand, where the combination of a huge area with a considerable yield gain makes for very large predicted increases in production. The simulated total global annual production increase in rainfed rice areas due to an increase in water availability of 10% is about 18 million tons of rough rice. Because of production constraints other than water, which were not considered in the simulations, this production increase would not likely be achieved by drought tolerance alone. However, this bias may be compensated for if increased drought tolerance leads to higher investments in, for example, fertilizers.

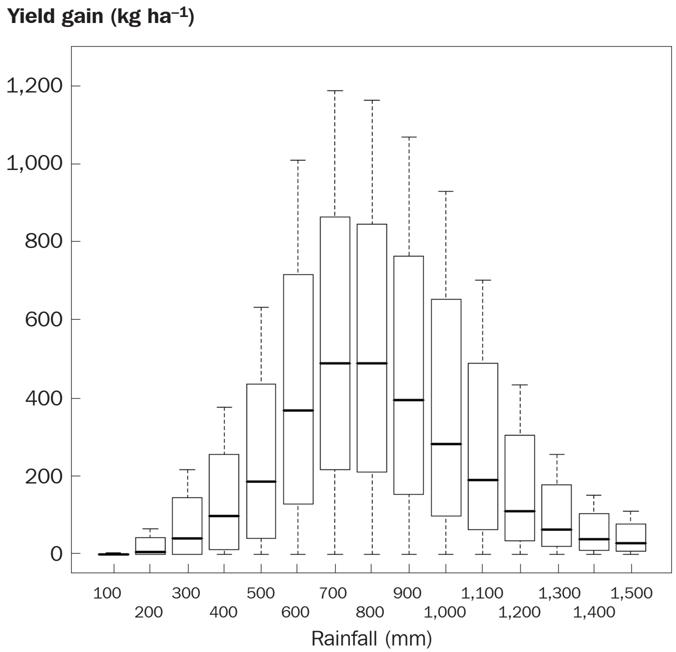

Fig. 6. Yield gain of rainfed lowland rice due to a hypothetical 10% increase in rainfall, by current rainfall. Box and whisker plot showing quartiles and median values.

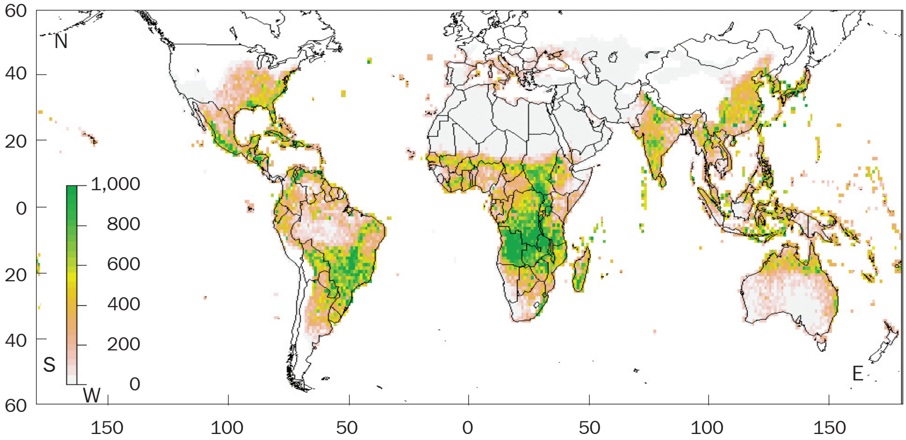

Fig. 7. Spatial distribution of yield gains (kg ha^{-1}) in rainfed rice with an increase in water availability of 10%.

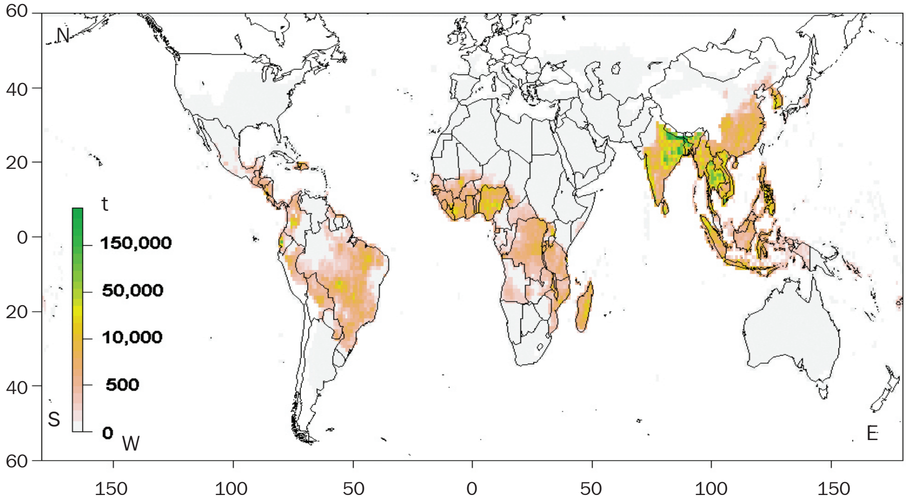

Fig. 8. Spatial distribution of production gains (tons) in rainfed rice with an increase in water availability of 10%.

Discussion

We have presented a preliminary analysis of drought stress in rainfed rice production. The modeling approach can, and will, be improved in many different ways. For example, we are working on incorporating insights on farmer behavior to improve our crop calendars (Shinji et al 2008) and allow for more adaptive variation to create distribution functions for management practices within each cell. The amount of detail that can be put in a broad regional study like this one is limited. Ideally, the regional work would help select sites for more detailed analysis (e.g., Fukai et al 2001), which could then be used to refine the regional modeling. In future work, we intend to look in more detail at several additional aspects, including different drought-coping mechanisms such as escape and daylength sensitivity.

In this study, we considered only rainfed lowland rice production. The hydrology of rainfed flooded rice fields does not only depend on rainfall but is also dependent on their position in the landscape (Haefele and Bouman, this volume). At the scale of our analysis, this probably does not matter that much. However, we do not really know, and in the future we would like to use hydrological models linked to the rice model to look at local variation in drought stress and yield. The highly unstable dynamics of hydrology, with frequent shifting between flooded and aerobic conditions within a paddy, impose a high amount of environmental variability and result in strong impact of the spatial variation in the toposequence on crop growth (Cooper et al 1999). We also ignored upland rice production systems that are more sensitive to drought as they do not have as much in field water storage capacity that can serve as a buffer.

Although we are continuing to refine our simulation modeling methods, it is equally, if not more, important to improve our simulation modeling method by contrasting, and perhaps integrating, the simulation modeling results with census data and the results obtained from studies of farmer behavior and households (e.g., Pandey and Bhandari, this volume). The simulation model results provide an easy way to reduce daily weather data to a single or a few indices. Rather than using them as truth, they could be used as predictors in a regression or data-mining modeling approach such as is commonly done in ecology ("ecological niche modeling," Elith et al 2006). However, to do so, we also need to develop broad-scale spatial data sets on farmer behavior in response to drought, and the effect of drought on yield in farmers' fields.

This study reported progress in using simulation models to characterize drought in rainfed rice. The results are preliminary and many more integrative studies are available. For example, drought-prone rainfed rice ecosystems were classified based on toposequence and water regime by Garrity et al (1986) and upland systems were described by Courtois and Lafitte (1999). Several studies have also previously discussed the biophysical characteristics of the rainfed lowland ecosystem and their implications in breeding (Mackill et al 1996, Fukai et al 2001, Wade et al 1999).

It would seem that our results somewhat underestimate drought risk. For example, in northwest Bangladesh, the average annual rainfall varies between 1,500 and 2,000 mm, with more than 200 mm of rainfall per month during the monsoon period (June to September), when transplanted aman rice (T. aman) is grown mostly under rainfed conditions. However, the erratic rainfall distribution causes drought frequently in this region, and results in yield losses that are generally higher than the damage caused by flooding and submergence (Towfiqul Islam 2008). A recent characterization and modeling study showed that the recurrence interval of drought is around 2–3 years, especially during the latest part of T. aman, generally recognized as terminal drought (Towfiqul Islam 2008). Short-duration varieties such as BRRI dhan 39 are generally used to escape terminal drought in this region. However, the risk of early droughts is also very serious, with a return period of 10 mm of rainfall deficit as high as 1.3 years in some districts, which requires a new set of drought-adapted T. aman rice varieties.

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Authors' address: International Rice Research Institute, Los Baños, Philippines.

Recent progress in breeding and genetics of drought resistance

Rice germplasm development for drought-prone environments: progress made in breeding and genetic analysis at the International Rice Research Institute

G.N. Atlin, R. Venuprasad, J. Bernier, D. Zhao, P. Virk, and A. Kumar

Drought is the most important constraint affecting yield in rainfed rice. Drought effects are most severe in unbunded upland fields and upper-toposequence bunded fields that infrequently accumulate standing water. Drought reduces productivity both through direct effects on biomass production and grain set and through delaying or rendering impossible crop management operations such as transplanting, fertilizer application, and weeding. There is substantial genetic variation for tolerance of drought stress, direct seeding in dry soil, and delayed transplanting. In areas where transplanting is likely to remain the major establishment system, varieties with tolerance of both drought and delayed transplanting are needed to reduce risk and increase productivity. In light-textured soils, direct seeding of drought-tolerant varieties in dry, unpuddled fields has the potential to eliminate the risk of transplanting failure and to advance maturity sufficiently to permit the production of a postrice crop. However, varieties for use in this establishment system must be highly weed competitive and have a high degree of tolerance of drought at the reproductive stage. The IRRI breeding program now routinely screens lines targeted at dry direct-seeding systems for rapid early biomass accumulation under aerobic conditions, a trait that has been shown to be closely associated with weed competitiveness. Lines targeted at transplanted systems are screened for yield under transplanting as 60-day-old seedlings. For both systems, advanced breeding lines are screened both for yield potential and for yield under continuous recurring drought stress after maximum tillering. IRRI research has confirmed that yield under drought stress has both a moderate heritability and a moderate positive correlation with yield potential, permitting the development of varieties combining high yield potential with stress tolerance. IRRI research has shown that direct selection for yield under drought stress, combined with selection for yield potential under favorable conditions, is an effective way to develop such cultivars. It has also been shown that hybrids are higher yielding than pure lines, on average, under both moderate lowland stress and delayed transplanting. Lines and hybrids combining high yield potential with yield of more than 2 t ha^{-1} under severe lowland stress, and more than 1.5 t ha^{-1} under severe upland stress, have been identified. Such varieties have the potential to reduce risk and increase overall productivity in drought-prone environments. Recent research indicates that, in many crosses, approximately 20–50% of the genetic variation for yield under severe stress is controlled by

factors that also affect yield potential. The remainder appears to be affected by relatively few genes with large effects that are detectable only in drought-stressed environments. Such genes may be used to increase the drought tolerance of widely grown varieties via marker-assisted backcrossing.

Drought

Drought stress occurs frequently in rice ecosystems that are either rainfed or rely on impounded surface water, affecting about 20–25 million ha worldwide. The eastern Indo-Gangetic Plain, with more than 17 million ha of rainfed rice area, is the worst affected region (Huke and Huke 1997). In this area, drought losses are most severe in the key rice-producing states of eastern India, as well as in neighboring areas of Nepal. Northeastern Thailand and Laos, with more than 3 million ha of drought-prone rainfed rice area, is the other severely drought-affected area in Asia (Pandey et al 2005). Drought also affects production on millions of hectares in irrigated areas dependent on surface irrigation, where river flows and water impounded in ponds, tanks, and reservoirs may be insufficient to irrigate the crop in dry years (Maclean et al 2002). In water-short areas, drought risk reduces productivity even in favorable years because farmers avoid investing in inputs when they fear crop loss (Pandey et al 2005).

Although water shortage is one of the most severe constraints to rice yield, limited effort has been devoted to the development of rice cultivars with improved drought tolerance. Breeding for drought tolerance is complicated by the intermittent occurrence of natural stress, the strong relationship between plant phenology and sensitivity to stress (Fukai et al 1999, Pantuwan et al 2002), and the specificity of tolerance mechanisms for particular soil hydrological environments. Genetic analyses of traits related to drought tolerance in rice conducted to date have usually reported the detection of many QTLs with relatively small effects (e.g., Babu et al 2003, Lanceras et al 2004), indicating that grain yield under drought stress in rice is a complex trait affected by many loci. Despite this complexity, substantial genetic variability for yield under drought stress has been documented in many types of field screen, and single QTLs with large effects on drought performance have recently been documented (Bernier et al 2007, Kumar et al 2007). Genetic variability has been detected in trials in which water was withheld at a defined phenological stage (e.g., Lafitte and Courtois 2002), populations were screened in dry seasons by stopping irrigation to the entire field on one date (Babu et al 2003, Venuprasad et al 2006, 2007), and populations were screened under wet-season stress imposed by draining paddies (IRRI, unpublished data; Kumar et al 2007). Variability exists both for drought tolerance per se (e.g., Pantuwan et al 2002, Lafitte and Courtois 2002) and for traits that confer adaptation to water-short environments, such as seedling vigor and weed competitiveness (Zhao et al 2006c). There is strong evidence that this variability can be exploited by screening lines for high yield under managed drought stress. Rice cultivars that combine improved yield under stress with high yield potential can be obtained by screening breeding lines for both yield potential in favorable environments and yield under managed stress. This approach has been successful in improving drought tolerance in several other crop species, notably maize (Bänziger et al 2006), but has been little used in rice. Recent evidence also indicates that there are alleles with large additive effects on yield under stress in rice that can be mobilized via marker-assisted selection (Bernier et al 2007). However, because the nature and timing of drought stress differ greatly among production environments, drought breeding efforts, whether based on phenotypic selection alone or incorporating molecular methods, must be tailored to meet the needs of farmers in specific water-short regions, land types, and production systems. The main objectives of this paper are therefore

- To identify particular drought-prone target environments and management systems.
- To clarify the physiological and agronomic effects of water shortage in drought-prone target environments.
- To outline screening and breeding strategies that can be used to develop drought-tolerant cultivars.
- To assess progress in identifying QTL alleles with large effects on yield under water stress, and assess their potential contribution to the development of drought-tolerant rice cultivars through marker-aided selection (MAS).

Target environments for drought germplasm improvement

Four major hydrological environments for rice production can be defined in terms of toposequence position, or the relative elevation of a rice field within a watershed consisting of terraced fields that drain into each other. Within distances of several hundred meters, the toposequence may include

1. Unbunded uplands that never retain standing water.
2. Bunded but drought-prone upper fields that retain standing water only briefly after a rainfall or irrigation.
3. Well-drained mid-toposequence fields that receive a reliable supply of water from fields higher in the watershed, but that rarely experience stagnant flooding.
4. Poorly drained lower fields in which water accumulates to depths of 1 m or more during the rainy season.

All four of these hydrological environments are often found within a small area in rainfed ecosystems. The latter three may also often be found within a single irrigation command area. Water shortage is mainly observed in unbunded uplands and bunded upper-toposequence fields. Drought stress in these environments varies in severity across years due to variability in the amount and distribution of rainfall, but occurs with predictable frequency in a given field, based on its toposequence position and soil texture. Yield variability under stress can be great even within a single field because of its variability in soil texture and levelness. This micro-scale variability among and within fields results in very large estimates of genotype × environment and residual error in the analysis of rainfed rice trials, thus complicating selection (Cooper et al 1999).

Over time, rice farmers develop a deep understanding of the hydrological behavior of their fields, allowing them to target varieties and management techniques to specific fields. In unbunded fields at the top of a toposequence, farmers grow short-duration, drought-tolerant upland rice varieties established via direct seeding. Varieties used in these systems are usually tall, unimproved, and of the *aus* (in South Asia) or tropical japonica (in Southeast Asia and West Africa) varietal groups. In upper bunded fields, farmers tend to grow short-duration, photoperiod-insensitive modern varieties that flower before the withdrawal of the monsoon, escaping late-season drought stress. In well-drained mid-toposequence fields, farmers usually grow semidwarf varieties developed for irrigated systems because of their high yield potential, and usually establish their crops via transplanting. In lower and flood-prone fields, farmers usually direct-sow tall, photoperiod-sensitive varieties that flower as the rains cease and thus stagnant water begins to decrease (Mackill et al 1996). Individual farmers often have fields at several toposequence levels, and thus often grow several varieties, each adapted to a particular hydrological environment.

The principal target environments requiring germplasm with improved drought tolerance are unbunded uplands and bunded upper fields at the top of a toposequence; drought occasionally occurs in lower fields but is relatively rare because these fields benefit from runoff and seepage from upper fields and usually remain saturated long after upper fields are dry. Unbunded uplands are highly drought-prone, but make up a relatively small and decreasing part of the South Asian rice area. Bunded upper fields are the most important target environment for drought tolerance breeding, because of both their extent and their potential for improved productivity. Rainfed rice breeding programs need to develop varieties with the duration, plant type, and stress tolerances required for this environment, which covers millions of hectares in most rice-growing areas. Rice crops in such fields were originally established via variants of the direct-seeding system known in eastern India as *beusani, biasi,* or *beushening* (Singh et al 1994), wherein dry seed is broadcast on moist soil; the fields are then re-plowed after seedlings are established and standing water has accumulated in the field, uprooting both weeds and rice seedlings. The rice seedlings are then re-rooted by hand or by running a plank over the field. Although the beusani system is still widely used in some areas, notably in the Indian state of Chhattisgarh, transplanting has spread extensively throughout eastern India in rainfed upper-toposequence fields since the general adoption of high-yielding semidwarf varieties in the 1970s. This new establishment technique is very risky due to the frequent failure of these upper-toposequence fields to accumulate sufficient standing water for timely transplanting, and because of frequent occurrence of drought stress after transplanting. This is an example of a change in crop management that has rendered the production system more sensitive to drought. A major research effort is now required to develop a more stable production system for upper bunded fields.

Physiological and agronomic effects of drought, and implications for germplasm improvement

Direct effects of water shortage on growth and yield

Effects of drought stress at flowering. The direct effects of water shortage on growth and yield can be acute, occurring at critical crop stages, or they may result from continually recurring nonsaturated conditions that reduce biomass accumulation and tillering over many weeks. The acute effects of drought immediately before and during flowering (Atlin et al 2006, Ekanayake et al 1990, Garrity and O'Toole 1994) are severe, so tolerance at this stage is particularly critical. This is especially true in upland rice, where the lack of standing water makes the crop vulnerable to brief periods of drought around flowering, possibly leading to near-complete spikelet sterility. For this reason, much research on drought tolerance has focused on tolerance of stress at the flowering stage. Substantial genetic variation exists within *Oryza sativa* for the trait (Atlin et al 2006). Some varieties have a high degree of tolerance of short periods of stress around flowering, whereas others experience markedly reduced seed set and harvest index. A set of varieties was evaluated at IRRI under rainfed upland conditions in the wet seasons of 2004 and 2005. In both seasons, drought at flowering resulted in severe stress between panicle initiation and anthesis. For a subset of lines with similar days to flower under nonstress conditions, mean yield and harvest index are presented in Table 1. In this set, yields ranged from 0.7 to 2.3 t ha^{-1}. Nearly all of the variation in yield was explained by variation in harvest index; lines that are high-yielding under stress, such as IR71525-19-1-1 and CT 6510-24-1-2, were able to maintain a high amount of seed set under stress at flowering. The physiological basis for this differential tolerance is unknown. Root architecture and root depth vary greatly among upland rice cultivars (e.g., Price et al 1997, Venuprasad et al 2002), but some deep-rooted upland cultivars, such as the traditional Philippine tropical japonica cultivar Azucena, are highly susceptible to dry soil conditions at flowering (unpublished data). Similar susceptibility to acute stress around flowering is observed in lowland rice, although stress may take longer to develop in a lowland field. In a lowland rice experiment repeated over two seasons in the mapping population CT9993/IR62266, stress at the flowering stage reduced yield by an average of 80% relative to a nonstressed control in a set of approximately 100 recombinant inbred lines (RILs). In this experiment, the relationship between yield under stress and maintenance of HI was very high, with a genetic correlation of 0.94 The range in tolerance of lowland stress in this population was also great; the highest-yielding line produced a mean yield of 1.39 t ha^{-1} over two years, nearly three times the trial mean (Kumar et al 2007).

Effects of intermittent stress throughout the season. Much less attention has been paid to the effects of growth reduction due to intermittent soil drying throughout the season in upper fields than to the acute effects of water shortage around flowering, but the former likely causes similar or greater overall losses, particularly in bunded upper fields that are managed by farmers as lowland (i.e., puddled and transplanted), but that do not maintain standing water. In puddled fields, relatively few rice roots penetrate the hardpan of the puddled soil layer, and most roots occur within the top 15

Table 1. Mean yield and harvest index of rice cultivars exposed to severe reproductive-stage stress under upland conditions: IRRI, WS 2004.

Designation	Harvest index	Yield (t ha^{-1})
IR71525-19-1-1	0.22	2.3
CT6510-24-1-2	0.19	2.0
UPL RI 7	0.16	1.9
Apo	0.18	1.7
IR77298-12-7	0.17	1.2
IR71700-247-1-1-2	0.16	1.1
IR77298-14-1-2	0.12	0.9
PR26406-4-B-B-2	0.09	0.8
PSBRc 82	0.11	0.7
IR72875-94-3-3-2	0.11	0.7
$LSD_{0.05}$	0.06	0.7

cm or less (Pantuwan et al 1997, Samson and Wade 1998). Therefore, when puddled fields dry at the surface, rice roots cannot access water that is deeper in the soil profile, and stress may develop quickly. Rice yields in such fields are closely related to the number of days in the growing season in which soil is saturated (Boling et al 2004, Haefele et al 2004). The ability to maintain biomass accumulation and seed set in relatively dry soils, and to acquire water from deeper soil, is therefore a key feature required in drought-tolerant varieties. Intermittent soil drying substantially reduces biomass production and therefore total yield potential. IRRI research has shown that there is substantial genetic variation in the ability of upland and lowland rice cultivars to maintain biomass accumulation in unsaturated water conditions. For example, in a set of lowland cultivars evaluated at IRRI under intermittently drained conditions in the wet season of 2005, yields averaged 1.6 t ha^{-1}, a reduction of more than 50% relative to the fully irrigated control. In this trial, there was a range in total biomass among cultivars of 4.1 to 7.4 t ha^{-1}. Variation in biomass was more closely related to final grain yield than was harvest index in this trial (Table 2).

Screening cultivars for tolerance of acute stress at flowering versus intermittent stress

Because crop phenological stages differ in their sensitivity to drought, researchers have devoted considerable efforts to the development of screening techniques that permit genotypes of different growth durations to be evaluated in common experiments at equivalent levels of stress at key stages such as flowering. These include techniques such as line-source irrigation (Lanceras et al 2004), which subjects cultivars to a constant stress gradient throughout the season, and field designs that permit each genotype to be irrigated independently (Lafitte and Courtois 2002), allowing stress to be targeted to a specific phenological stage for each cultivar in the trial. However, these methods are not practical in a breeding program that must screen hundreds

Table 2. Cultivar differences in yield, harvest index, and biomass production in an intermittently-dried lowland field: IRRI, WS 2005.

Designation	Harvest index	Biomass (t ha^{-1})	Yield (t ha^{-1})
IR70213-10-CPA 4-2-2-2	0.28	7.6	2.1
IR79670-125-1-1-3	0.26	7.3	1.9
PSBRc 80	0.30	5.2	1.6
PSBRc 14	0.34	4.9	1.7
IR36	0.31	4.2	1.3
PSBRc 82	0.40	4.1	1.6
LSD$_{0.05}$	0.13	2.5	0.4

of lines. The IRRI breeding program screens for drought tolerance using protocols (described below) in which stress is repeatedly imposed on a large nursery or trial on a uniform date, shortly after transplanting in lowland rice and at around maximum tillering in upland rice, with cycles of stress and re-irrigation repeated until harvest. Variety means in screens of this type are highly correlated with means from trials in which stress is precisely applied at the sensitive flowering stage (IRRI, unpublished data). They are also at least as repeatable as means from nonstress trials (Venuprasad et al 2007, Bernier et al 2007).

Effects of drought on crop management and agronomic practices

Land preparation, transplanting, fertilizer application, and weed control in lowland rice production are all dependent on the presence of a standing water layer in the paddy. If standing water is not present, these operations may be delayed or omitted, resulting in large yield losses, even though plants may not have suffered physiological water stress. Losses from these management disruptions may be as great as those from direct drought damage. Cultivars differ in their sensitivity to these management disruptions. These differences can be exploited in the development of more resilient varieties for drought-prone environments.

Transplanting delay. Transplanting is the management step that is most vulnerable to water shortage. The optimum age of seedlings at transplanting is 2 to 4 weeks old, but rainfed farmers must often delay transplanting due to water shortage, and therefore plant seedlings that are much older than optimum. Farmers cannot transplant until sufficient water accumulates in fields to permit puddling (usually 400–500 mm of rainfall); often, this may not occur until seedlings are 60 to 80 days old. Such delays result in large yield losses because of reductions in both panicle number and weight. In experiments conducted at IRRI in 2005, transplanting 65-day-old as opposed to 22-day-old seedlings resulted in a yield reduction of more than 50%, averaged across 125 cultivars. Yield reductions due to delayed transplanting were experienced on this scale in large areas of eastern India in 2004, and in the Nepali *terai* and adjoining regions of Uttar Pradesh in 2006. Even high-rainfall regions that are not truly drought-prone, such as southern Cambodia, may experience severe losses due to delayed transplanting resulting from an early-season pause in the monsoon.

Weed management. Water shortage also affects weed management. Standing water in lowland fields after sowing or transplanting suppresses the germination of weeds. Under the nonflooded, aerobic conditions characteristic of upland or drought-affected lowland fields, weeds germinate freely. Most upland weed species grow more quickly than rice in nonsaturated soils, resulting in greater competition from weeds under drought conditions. The widespread indigenous eastern Indian rainfed lowland establishment and weed-management practice of *beushening* (described above) (Singh et al 1994) is also highly sensitive to early drought stress, as the uprooting and replanting process requires the presence of standing water in the field. Early drought therefore results in a failure of weed control in this system. Extensive genetic variation among rice cultivars with respect to weed competitiveness has been documented both for upland (Zhao et al 2006a) and lowland (Haefele et al 2004) systems, but little effort has been made to exploit this variation in the development of cultivars for water-short environments. Recently, however, Zhao et al (2006b) showed that weed-suppressive ability and weed competitiveness under upland conditions are strongly associated with rapid seedling growth in the first 4 weeks after sowing, a trait that is easily scored and for which substantial variability exists within and among the major rice germplasm groups (Zhao et al 2006c). Thus, selection for rapid early vegetative growth can be relatively easily incorporated into breeding programs that aim to develop cultivars for aerobic or direct-seeded systems.

Cultivar development for drought-prone environments

The analysis of drought hydrological environments and production systems described above indicates that reducing drought risk in rainfed production environments will require the development of two different types of germplasm:

- In both unbunded uplands and in the uppermost bunded fields, which almost never accumulate standing water, varieties are required that combine adaptation to dry direct seedling, the ability to maintain biomass production at a high rate in soils that are usually below field capacity, tolerance of severe drought stress at flowering, and high yield potential under favorable conditions. These varieties, which differ from traditional upland rice varieties in their input responsiveness and yield potential that allow them to achieve yields of 4–5 t ha^{-1} under favorable conditions, are often referred to as aerobic rice.
- On slightly lower fields, where transplanting is usually possible, but may be delayed because of water shortage, and where stress may occur at any point after establishment, varieties are needed that combine high yield potential with tolerance of delayed transplanting, and the ability to maintain biomass production and seed set in soils that are frequently unsaturated and usually below field capacity.

These two cultivar types are being developed by IRRI's aerobic rice and drought-prone lowland breeding programs. Overall, the most effective strategy for improving drought tolerance for these environments has proven to be *direct selection* for grain yield under water stress (Venuprasad et al 2006, 2007). Screening and breeding strategies are described below.

Developing cultivars with improved lowland drought tolerance for bunded upper terraces

The most drought-affected lowland fields are upper-toposequence bunded fields that are established by transplanting or traditional broadcasting methods. Critical traits for these fields include the ability to maintain biomass accumulation in intermittently dry fields, tolerance of severe stress at flowering, tolerance of delayed transplanting, and responsiveness to favorable conditions when they occur.

Screening for drought tolerance. Bunded (lowland) fields regularly affected by drought are usually upper-toposequence fields with light to medium soil texture. These fields are without standing water for much of the growing season, and may dry out repeatedly. Screening of cultivars targeted at this environment should mimic these intermittently dry conditions. Effective screening for lowland drought tolerance can be done even in the wet season in trials situated in upper light-textured fields that can easily be drained; in such wet-season screens, planting may be delayed to increase the possibility that the monsoon will withdraw before flowering, increasing the chances of imposing severe flowering-stage drought stress (e.g., Kumar et al 2007). Care should be taken to ensure that the field used is at the top of the toposequence, and that there is no higher field from which water flows into the drought-screening site. Because the objective of screening is to identify cultivars with improved yield under stress, such screening is conducted at IRRI in replicated trials in plots 5 m in length to achieve adequate precision. Seedlings are transplanted into puddled soil, and then the trial should be drained 7 days after transplanting. The field is allowed to dry until the soil cracks and/or the surface is completely dry. The field is not irrigated again until the local check variety is wilting severely, and the water table is at least 1 m below the surface. If tensiometers are installed, the field is irrigated when soil water tension = 40–70 kPa at a depth of 20 cm. When these conditions are achieved (the time needed for this to occur varies with soil texture, rainfall, and evapotranspiration), the field is then re-irrigated by flash flooding. One day after re-irrigation, the field is drained again. The cycle of stress followed by re-irrigation and drainage is repeated until the field is finally drained for harvest. Drought tolerance is expressed simply as the yield produced by a cultivar under stress.

Screening under this type of managed stress has identified large differences among lowland breeding lines and mega-varieties in yield under stress at IRRI (Table 3). Several lines (e.g., the IR64-derived line IR77298-14-1-2 and the hybrid IR80228H) have been identified that are comparable in yield potential with current elite irrigated varieties under nonstress conditions, but that outyield them substantially under drought stress. Screening for grain yield under drought stress has now been incorporated as a routine cultivar evaluation step by IRRI and by several Indian

Table 3. Days to flower, harvest index, and yield of medium-duration varieties and breeding lines under severe intermittent lowland drought stress and full irrigation: IRRI, 2006 dry season.

Designation	Days to flowering		Harvest index		Yield (t ha^{-1})	
	Stress	Nonstress	Stress	Nonstress	Stress	Nonstress
IR77298-14-1-2	94	85	0.21	0.40	1.2	3.3
IR80461-B-7-1	95	84	0.22	0.37	1.1	3.7
IR80228 H	101	85	0.27	0.46	0.9	5.8
PSBRc 82	104	91	0.10	0.36	0.3	2.6
Trial mean	100	88	0.10	0.34	0.4	2.2
LSD$_{0.05}$	8	2	0.10	0.16	0.4	0.9

breeding programs in collaboration with the IRRI-India Drought Breeding Network, a collaborative network serving drought-prone rainfed environments. In 2005, this network tested a number of breeding lines developed at IRRI as well as at different national research institutes in India for their performance under drought. These lines were screened in alpha lattice designs with three replications under fully irrigated conditions and two levels of stress. In one stress level, fields were drained just after transplanting, water from rains was never allowed to stand, and the trial was never irrigated. These experiments generally experienced severe stress resulting in at least a 70% reduction in mean yield as compared with control yields. In the second stress level, fields were drained 35–40 days after transplanting with the aim of screening the lines for tolerance of reproductive-stage stress. The mean yield reduction in these moderately-stressed experiments ranged from 30% to 60%. Screening under severe drought, moderate drought, and flooded control at Raipur identified breeding lines of 100–120 days' duration that had yield potential of 4.0–5.2 t ha^{-1} under nonstress conditions and produced grain yields of 1.7–2.1 t ha^{-1} under severe drought stress (Table 4). In the group of 120–140 days' duration, breeding lines with yield potential of 6.3 t ha^{-1} under flooded control and yields of up to 1.9 t ha^{-1} under severe drought stress were identified (Table 5). The screening also showed that the widely grown rainfed variety Swarna was moderately tolerant of lowland drought, whereas the related variety Sambha Mahsuri was extremely susceptible to drought stress.

Screening for tolerance of delayed transplanting. Delayed transplanting due to drought is probably the main cause of yield loss in most rainfed lowand systems, but tolerance of delayed transplanting has rarely been systematically evaluated or incorporated as a rice breeding objective. Variability for tolerance of delayed transplanting appears to be large, even in photoperiod-insensitive germplasm. In an evaluation in the 2005 wet season of 125 photoperiod-insensitive varieties with medium duration transplanted when seedlings were 65 days old, cultivar mean yields ranged from 0.3 to 3.3 t ha^{-1}. Some elite breeding lines and cultivars yielded well when normally

Table 4. Grain yield, days to flower, and harvest index of medium-duration (120–140 days) varieties and breeding lines under three levels of water stress: IRRI-India Drought Breeding Network, 2005 wet season. Mean of cultivars over 7, 3, and 1 trial in southern and eastern India for nonstressed, moderately stressed, and severely stressed trials, respectively.

Designation	Days to flowering Stress level			Harvest index Stress level			Yield (t ha^{-1}) Stress level		
	None	Moderate	Severe	None	Moderate	Severe	None	Moderate	Severe
Tolerant lines and varieties									
Baranideep	82	87	87	0.42	0.40	0.38	5.5	3.9	1.4
CB00-15-24	81	83	82	0.40	0.40	0.36	5.0	3.1	1.4
IR74371-3-1-1	83	83	88	0.41	0.42	0.34	5.0	3.9	1,2
Widely grown varieties									
MTU 1010	86	92	91	0.28	0.21	0.13	2.9	1.9	0.6
IR64	87	90	90	0.41	0.35	0.17	5.2	2.9	0.5
IR36	85	97	94	0.41	0.27	0.04	4.2	2.0	0.1
Trial mean	84	89	91	0.38	0.32	0.22	4.6	2.8	0.8
$LSD_{0.05}$	4	5	3	0.05	0.08	0.11	0.8	0.9	0.4

Table 5. Grain yield, harvest index, and days to flowering of 120–140 days' duration entries from the IRRI-India Drought Breeding Network: Raipur, WS 2005.

Designation	Harvest index			Days to flowering			Yield (t ha^{-1})		
	Control	Moderate stress	Severe stress	Control	Moderate stress	Severe stress	Control	Moderate stress	Severe stress
ARB 6	0.37	0.43	0.4	79	78	81	6.7	4.3	1.9
IRMBP-2	0.38	0.32	0.35	82	84	85	6.1	3.2	1.3
Mahamaya	0.34	0.19	0.14	92	93	96	6.5	1.9	0.6
PSBRc-9	0.42	0.42	0.37	90	89	91	5.8	4.3	1.6
Sambha Mahsuri	0.41	0.09	0.02	103	111	–	6.7	0.8	0.0
Swarna	0.38	0.25	0.34	103	110	126	6.0	2.1	1.3
Swarna/IR42253-54	0.42	0.33	0.38	83	85	80	6.4	2.8	1.7
$LSD_{0.05}$	0.04	0.06	0.07	1	1	5	0.7	0.6	0.4

Table 6. Agronomic performance of 10 hybrids versus 115 pure lines when transplanted at 22 or 65 days after sowing: IRRI, 2005 wet season.

Cultivar type	Days to flowering		Height (cm)		Harvest index		Yield (t ha^{-1})	
	Seedling age at transplanting (d)							
	22	65	22	65	22	65	22	65
Hybrid	85	114	115	90	0.41	0.38	5.0	2.7
Inbred	82	113	119	92	0.37	0.28	3.4	1.5
Pr > F.	ns[a]	ns	ns	ns	0.0012	<0.0001	<0.0001	<0.0001

[a] ns = nonsignificant.

transplanted, but poorly when delay-transplanted. A notable example is IR77298-14-1-2, a tungro-resistant derivative of IR64, which yielded 4.0 t ha^{-1} under normal transplanting, but only 1.8 t ha^{-1} under delayed transplanting. In contrast, a hybrid, IR80642H, yielded 4.4 t ha^{-1} under normal transplanting and 3.3 t ha^{-1} under delayed transplanting. In general, hybrids were found to be more tolerant of delayed transplanting than were inbreds (Table 6).

Developing cultivars with improved drought tolerance for unbunded uplands

Upland rice is grown as a subsistence crop in unbunded upper fields by some of the poorest farmers in Asia. Upland rice growers use few improved varieties and, because of risk of crop loss due to drought or weed pressure, apply only small amounts of fertilizer to their fields. Recently, studies in traditional upland rice-growing areas of Yunnan (Atlin et al 2006) and Laos (Saito et al 2006) demonstrated that improved upland rice varieties have at least 50% higher yield potential than traditional cultivars, and can serve as the basis for more productive and sustainable upland rice-based cropping systems. However, since upland systems are almost exclusively rainfed, adoption of such systems will depend on the development of varieties that combine high yield potential with high levels of drought tolerance and weed competitiveness.

Screening for tolerance of upland drought stress. Strategies for drought-tolerance screening under upland conditions are similar to those described above for lowland management. Most upland varieties are photoperiod-insensitive, so, if temperatures permit, dry-season screening is the preferred option for reliably imposing stress. Many upland varieties have a moderate degree of vegetative drought tolerance, but are often highly susceptible to stress around flowering. For this reason, screening protocols should emphasize tolerance of stress at flowering. At IRRI, drought screening is conducted in replicated yield trials of fixed lines that have been previously selected for yield potential and disease resistance. Screening is conducted in an unbunded well-drained field at the top of a toposequence. No irrigated or flooded trials are planted above the drought-screening site, and lines are screened in trials with at least two replicates. Trials are direct-sown into dry soil. The field is irrigated to maintain soil water potential near field capacity until canopy closure, or for about 50 days after seeding (DAS), and the frequency of irrigation is then reduced until harvest. Irrigation is withheld until the soil surface is completely dry, susceptible check varieties are severely wilted, and soil water tension reaches 50 to –70 kPa at a depth of 30 cm. When the target level of soil dryness and plant stress is reached, the field is liberally irrigated to saturate the root zone. Per irrigation, this requires around 40–60 mm of water.

There is evidence that differences in drought tolerance measured in this screen are predictive of differences observed under natural stress in the target population of environments. For example, 30 varieties were screened under severe upland stress artificially imposed at IRRI in the dry season (DS) of 2005. These same varieties were screened under rainfed upland conditions at IRRI in the wet season (WS) of 2004 and WS of 2005. In both of these years, severe drought stress occurred at flowering during the wet season. The mean correlation between variety means for grain yield in the dry-season stress screen and under natural stress in the wet season was 0.87, indicating that the ability of the artificial drought screen to predict performance under natural stress was high (IRRI, unpublished data).

Selection of breeding lines under artificial stress has been shown to result in gains under natural stress in wet seasons. Venuprasad et al (2007) screened several hundred lines from the crosses Apo/IR64 and Vandana/IR64 in the DS of 2003. The lines were evaluated for grain yield under both severe upland stress and irrigated control conditions. Selected lines from both the stress and the irrigated control screens were then evaluated under natural stress at IRRI in the WS of 2004 and 2005. Yield gains under natural stress were greater in the subset of lines selected under artificial stress than under fully irrigated conditions. Selection under stress gave no gains under nonstress conditions nor did it reduce yield potential.

Screening for weed competitiveness. Upland rice cultivars that compete well against weeds are often thought to be tall, rapid in early growth, and have droopy leaves and high specific leaf area. These traits have been linked to low yield potential in some studies (Jennings and Aquino 1968, Kawano et al 1974), but not in others (Garrity et al 1992, Ni et al 2000, Fischer et al 2001). More recently, Zhao et al (2006b) have shown that differences in cultivar weed competitiveness in direct-sown rice are largely determined by differences in the rate of seedling biomass accumulation in the first 4 weeks after sowing. They observed that, averaged over 3 years, there was a twofold difference between the most and least competitive cultivars in weed biomass at 9 weeks in plots that were hand-weeded once at 3 weeks after sowing, and that there was no trade-off between yield potential and weed competitiveness. Improved weed competitiveness can be selected for in replicated trials by visually rating advanced breeding lines for total biomass at 4 weeks after sowing (Zhao et al 2006b). Screening for seedling biomass accumulation has been incorporated as a routine screening step in the IRRI rainfed and aerobic rice breeding programs. Cultivars with high seedling biomass accumulation tend to be erect, moderately drought-tolerant, and derived from the indica and *aus* germplasm groups.

Direct seeding to reduce drought risk in drought-prone upper fields

As noted above, rice establishment either by transplanting or the traditional beushening/biasi practice in bunded upper fields frequently leads to heavy crop yield loss because of delayed transplanting, exposure of the transplanted seedlings to early drought, or heavy weed pressure. In crops where establishment has been delayed due to lack of standing water in fields, the risk of drought occurring during the reproductive stage or grain filling is also increased. Direct seeding of unsprouted seed in dry soil, with herbicide-based weed control, may be a useful alternative to transplanting or beushening in areas where early-season drought is frequent.

Direct seeding can be undertaken in dry or moist soil starting with the earliest rains, and therefore allows establishment to take place 4 to 6 weeks earlier than is possible in puddled transplanted systems. Early establishment reduces drought risk during flowering and grain filling associated with early withdrawal of the monsoon, and, because direct-sown crops mature approximately 10–14 days earlier than transplanted crops seeded on the same date, increases the probability of successfully establishing a postrice rainfed crop. Direct-seeded establishment also eliminates the risk associated with delayed transplanting, which occurs when rainfall is insufficient for main-field puddling by the time seedlings are ready to be removed from the nursery bed; planting overaged seedlings due to early-season drought is a major cause of yield reduction in light soils and upper rainfed terraces.

Cultivars differ substantially in their adaptation to dry direct-seeded establishment in nonsaturated soils. Component traits include weed competitiveness, seedling vigor, ability to maintain biomass development in intermittently dry fields, and tolerance of late-season drought. The development of adapted cultivars with these traits is therefore an important element in the design of successful direct-seeding establishment systems in rainfed upland and shallow lowland systems. Such cultivars are often referred to as *aerobic rice*, and are also potentially useful in irrigated rice systems where water availability is limited (Bouman et al 2006).

A new generation of aerobic-adapted varieties for direct-seeded systems has been identified with yield potential of 4–5 t ha^{-1} but that produce yields of more than 1 t ha^{-1} when subjected to severe intermittent stress bracketing the entire reproductive period. The yield potential of these materials is not greater than that of current elite aerobic adapted variety Apo or the lowland variety PSBRc 80, but yields under moderate drought stress are three- to fourfold higher (Table 7).

Designing cultivar development programs that can combine drought tolerance with yield potential

For the drought-prone target environments described above, breeding programs must combine selection under stressful conditions with selection for yield potential because farmers want cultivars that are both drought-tolerant and have high yield potential in favorable years. It can be useful to think of the breeder's task as raising both the "ceiling" of yield potential that can be achieved in favorable years and the "floor" yield that can be protected under drought conditions.

Table 7. Grain yield of elite aerobic-adapted varieties and a lowland-adapted check (PSBRc 80) evaluated under aerobic management with severe intermittent stress applied following maximum tillering: IRRI, DS 2005.

Designation	Nonstress yield ($t\ ha^{-1}$)	Stress yield ($t\ ha^{-1}$)	Days to flowering (nonstress)
IR78875-190-B-1-3	4.6	0.8	81
IR71525-19-1-1	4.2	1.4	85
IR78875-131-B-1-3	4.1	1.0	85
IR78875-131-B-1-2	4.0	1.0	79
IR74371-54-1-1	4.0	1.1	75
Apo	3.4	0.2	80
PSBRc 80	1.0	0.1	78
$LSD_{0.05}$	1.1	0.3	

Substantial evidence indicates that these goals are not mutually exclusive. Most studies in which large populations of unselected lines have been screened under both stress and nonstress conditions show that there is a moderate to large positive correlation between yield under drought stress and yield potential under favorable conditions. Atlin et al (2004) surveyed 10 experiments in which populations of random recombinant inbred or doubled haploid lines were evaluated under both water stress and control, with a mean reduction of 65% due to water stress. They reported genetic correlations for yield across stress levels that ranged from 0.35 to 0.91, averaging 0.67.

Even when reductions due to stress are extreme, genetic correlations for yield across stress levels tend to be positive and often quite high. Kumar et al (2007), in an experiment involving a population of doubled-haploid lines from the cross CT9993-5-10-1-M/IR62266-42-6-2 evaluated over 2 years under lowland conditions in a stress regime that reduced yield by 80% relative to a well-watered control, observed a genetic correlation of 0.8 across stress levels for yield, indicating that two-thirds of the genetic variation for yield under stress involved factors that also affected yield potential. Venuprasad et al (2007) evaluated five large populations under upland drought stress and lowland nonstress conditions and found that, on average, stress reduced yield by more than 64% but still the genetic correlation between yields in stress and nonstress was 0.48. In an upland experiment involving the Vandana/Way Rarem population, in which mean yield reduction due to water stress over 2 years was 88%, the genetic correlation for yield across stress levels was 0.44 (Bernier et al 2007). In general, even under extremely stressful conditions, perhaps 30–50% of the genetic variance for yield under drought in random mapping populations is due to factors that also affect yield potential, such as partitioning of biomass to grain. The remaining 50–80% of genetic variation for yield under severe stress is due to factors that affect only drought tolerance rather than yield potential. To ensure that these factors are screened for during the selection process, it is important that the yield of managed drought stress trials be reduced by at least 50% relative to nonstress controls (Venuprasad et al 2007, Pantuwan et al 2002).

The moderate positive correlation between yield under optimal conditions and yield under severe drought stress in mapping populations, which are sets of unselected lines, should not be taken as evidence that selection for yield under stress is unnecessary in the development of drought-tolerant cultivars. On the contrary, most elite cultivars developed for irrigated or favorable rainfed systems have very poor drought tolerance (e.g., Table 4). The moderate positive correlation is evidence, however, that it is feasible to produce cultivars combining high yield potential and improved drought tolerance.

How should a breeding program that aims to produce such cultivars be organized? The key feature of a successful drought breeding program is the incorporation of a managed-stress screening step early in the selection process, preferably at the initial replicated testing stage (because the heritability of yield under stress, like yield under well-watered conditions, is relatively low, only replicated screening should be used as a basis for selection; selection for yield under stress or nonstress conditions in unreplicated nurseries or on a single-plant basis is likely to be ineffective). In a well-conducted managed-stress drought screen, the repeatability of genotype yield estimates is usually similar to or only slightly less than in well-watered trials (at IRRI, trials conducted under severe drought stress often have higher repeatability than well-watered trials). Therefore, selection of lines for advancement can be based on means over stress and nonstress trials. Plot yield measurements within stress levels should be standardized (i.e., divided by their within-trial standard deviation) before analysis for such selection, so that means from nonstress trials, which may be three- to fivefold higher than means in stress trials, do not overwhelm the information from the stress trials; selection on the basis of raw means over stress levels would be heavily weighted in favor of performance under nonstress conditions. Selection on the basis of mean performance over stress levels may not, however, be appropriate in situations where selection for yield potential is done in the wet season and selection for stress tolerance is conducted only in the dry season. In this case, it may be appropriate to screen first for yield potential in the wet season, subjecting only those lines with high yield potential to drought tolerance screening in the dry season. Choice of parents is a critical step in designing crosses for drought tolerance breeding. To maximize the prospects for selecting progeny combining high yield potential with improved drought tolerance, at least one parent in the cross should be known to be drought-tolerant or to produce drought-tolerant offspring. Relatively little information is available on such potential donors. Experience at IRRI has shown that donors of upland drought tolerance are not necessarily useful donors for lowland drought tolerance; donors conferring a form of tolerance appropriate to the target environment should be used. A list of such donors, as well as some highly susceptible check varieties, is presented in Table 8.

The use of drought-tolerant parents and application of the screening methods described above have resulted in the development or identification of lines combining improved stress tolerance with high yield potential at IRRI. Table 9 presents partial results from IRRI's 2006 dry-season trials of advanced rainfed lowland breeding lines

Table 8. Drought tolerance donors and susceptible checks identified through testing at IRRI.

Genotype	Adaptation	Drought tolerance level	Yield potential	Notes
IR71525-19-1-1	Upland	Highly tolerant	Low	Improved japonica type with high vegetative- and reproductive-stage drought tolerance, medium duration
IR55419-04	Upland	Moderately tolerant	Moderate	Improved indica type with excellent upland adaptation and early vigor, medium duration
IR55423-01 (also PSBRc 9, Apo)	Upland and lowland	Moderately tolerant under upland and lowland conditions	High	High yield potential under both favorable upland and lowland conditions, long duration
IR74371-46-1-1	Upland	Moderately tolerant	Moderate	Aerobic-adapted rice with moderate drought tolerance, medium duration
Vandana	Upland	Highly tolerant	Low	Improved eastern Indian upland rice derived from an aus/japonica cross, short duration
IR71524-44-1-1	Upland	Highly tolerant	Low	Improved japonica type with high vegetative- and reproductive-stage drought tolerance, medium duration
UPLRI-5	Upland	Highly susceptible	Moderate	Highly susceptible upland variety
IR77298-14-1-2	Lowland	Moderately tolerant	Moderate	IR64 derivative, tungro-resistant in addition to drought-tolerant
IR81047-B-106-4-3	Lowland	Moderately tolerant	High	Medium-duration indica line combining moderate drought tolerance with high yield potential
IR77843H	Lowland	Moderately tolerant	High	Drought-tolerant hybrid
IR80228H	Lowland	Moderately tolerant	High	Drought-tolerant hybrid
IR36	Lowland	Highly susceptible	Moderate	Widely grown short-duration lowland variety, highly susceptible
IR64	Lowland	Highly susceptible	Moderate	Widely grown short-duration lowland variety, highly susceptible

Table 9. Yield under lowland drought stress and fully irrigated conditions of medium-duration lines selected either under nonstress conditions only or under both stress and nonstress conditions: IRRI, dry season 2006.

Designation	Selection history	Stress yield	Nonstress yield
		($t\ ha^{-1}$)	
IR80461-B-79-3	Stress and nonstress	1.1	5.0
IR72	Nonstress only	0.7	3.4
PSBRc 82	Nonstress only	0.3	3.3
IR80461-B-7-1	Stress and nonstress	1.3	4.5
$LSD_{0.05}$		0.4	1.2

in the medium-duration group. Some lines that had been selected under both stress and nonstress conditions significantly outyielded, under both stress and nonstress conditions, elite irrigated varieties selected only under optimal conditions.

Hybrid rice varieties: an option for drought-prone lowland fields

Hybrid varieties appear to offer a route to combining improved tolerance of drought stress with high yield potential, particularly in drought-prone lowland fields or fields where transplanting is often delayed. In replicated field experiments conducted at IRRI during the dry seasons of 2003 through 2006, seven hybrids not previously selected for drought tolerance were compared with elite pure lines (also not selected for drought tolerance) from the IRRI irrigated ($n = 31$) and aerobic ($n = 4$) breeding programs under (1) full irrigation; (2) a nonstress alternate wetting-and-drying irrigation protocol, with the water table maintained within 15 cm of the soil surface; and (3) the intermittent lowland drought stress protocol described above. Mean yields of the three treatments over two years were 6.3, 5.6, and 1.8 t ha^{-1}, a 71% yield reduction for the stress protocol relative to full irrigation (Table 10). The hybrids outyielded pure lines from both the irrigated and aerobic breeding programs under all three irrigation regimes; under the stress protocol, the mean yield advantage of the hybrids relative to the pure lines selected under similar irrigated management was 1.2 t ha^{-1}. The advantage of hybrids is both proportionately and absolutely greater under moderate stress than under fully irrigated conditions. The tolerance of hybrids of moderate water stress and, as noted earlier, delayed transplanting, combined with their high yield potential in favorable environments, may have contributed to their rapid adoption in eastern India, where they have been introduced by the commercial seed sector over the past five years. Particularly in the drought-prone shallow lowland areas of the poorest states in the region, including Jarkhand, Bihar, Uttar Pradesh, and Chhattisgarh, smallholders have been eager to replace short-duration but drought-susceptible varieties such as IR64 and IR36 with hybrids.

Table 10. Agronomic trait means under full irrigation, alternate wetting and drying (AWD), and severe water stress of hybrids, pure lines selected under full irrigation, and pure lines selected under upland management: IRRI, 2003-04.

Variety type	Grain yield (kg ha^{-1})			Days to flower			Height (cm)		
	Full irrigation	AWD	Severe stress	Full irrigation	AWD	Severe stress	Full irrigation	AWD	Severe stress
Hybrids	7,321*	6,348*	2,753**	84**	85**	85*	97	86	76
Lowland lines	6,185	5,527	1,514	91	92	96	104	96	81
Upland lines	5,751	5,043	2,356**	82**	83**	82**	106	96	86
Mean	6,330	5,616	1,794	89	90	93	103	94	81

*,** Single df contrast with mean of lowland lines significant at $P = 0.05$ and $P = 0.01$, respectively.

Prospects for marker-aided selection for drought tolerance in rice

A relatively few improved varieties, including Swarna, Samba Mahsuri, IR36, IR64, BR11, and MTU 1010, sometimes referred to as "mega-varieties" (Mackill 2006), together now account for much of South Asian rainfed rice production. Most of these varieties are valued for their quality, marketability, and yield potential under favorable conditions. Extensive multienvironment testing by the IRRI-India Drought Breeding Network has shown that most of these important varieties are highly susceptible to even moderate drought stress (e.g., Tables 4 and 5). However, these rainfed mega-varieties will be very difficult to be replaced by more drought-tolerant genotypes unless they are matched in terms of quality and agronomic performance in favorable years.

Prospects for the adoption of drought-tolerant varieties will be improved if yield under stress can be enhanced through the development of mega-varieties introgressed with a small number of genes for drought tolerance via marker-assisted selection (MAS), leaving the rest of the desirable recurrent-parent genotype largely intact, a strategy that has been highly successful in rice for abiotic stresses such as submergence (Xu et al 2006). Until recently, however, the possibility of finding this type of gene in rice appeared to be slight. Genetic analyses of traits related to drought tolerance in rice conducted to date have usually reported the detection of many QTLs with relatively small effects (e.g., Babu et al 2003, Lanceras et al 2004), leading most researchers working in the field to conclude that grain yield under drought stress in rice is a highly complex trait affected by many loci with small effects, making progress from MAS unlikely. Efforts to introgress chromosomal regions with small or moderate effects on secondary root traits thought to be related to drought tolerance have not succeeded in significantly improving yield under stress (Shen et al 2001, Steele et al 2006), further increasing skepticism about the potential for MAS-based approaches. However, the bulk of the data on which these conclusions were based were derived from only two mapping populations, Azucena/IR64 and CT9993-5-10-1-M/IR62266-42-6-2. These experiments also attempted to introgress large chromosome segments carrying a putative QTL, rather than a small fine-mapped region, and therefore are likely to have been affected by linkage drag. Use of fine-mapped targets could be more successful.

Recently, IRRI initiated a broader survey to systematically identify genes or oligogenic combinations with large effects on yield under drought stress, both in donors known to have high yield under stress and in random donors. Evidence is now accumulating that a relatively small number of genes can have a large effect. Lafitte et al (2006) reported that, in backcross populations derived from the susceptible recurrent parent IR64 crossed to unselected donors and mass-selected in the BC_2F_2 for yield under stress, lines were selected that significantly outyielded IR64 under moderate stress. In another study, BC_3-derived sister lines from the cross IR77298, developed with IR64 as a recurrent parent and the tungro-resistant pure-line variety Aday Selection as a donor, were shown to differ substantially in yield under severe lowland stress, despite sharing a coefficient of co-parentage of more than 0.9 (Venuprasad et al 2007, IRRI, unpublished data). In an upland rice population derived from the cross Vandana/Way Rarem, a single QTL accounted for more than 50% of genetic variation for yield under severe upland stress over 2 years, but had no effect under nonstress conditions (Bernier et al 2007). The allele conferring improved tolerance more than doubles the mean yield of homozygotes under stress (from approximately 0.2 to 0.6 t ha^{-1}). In lowland screening of a population derived from the cross CT9993-5-10-1-M/IR62266-42-6-2, a single QTL located near the *sd-1* locus on chromosome 1 accounted for more than 30% of genetic variation for yield under severe reproductive-stage stress, but only 4% under nonstress conditions (Kumar et al 2007). It should be recalled from the discussion in the section "Defining cultivar development programs" that approximately half of the genetic variance for yield under stress is due to variation in yield potential expressed under both stress and nonstress conditions. Thus, single genes explaining 30–50% of the genetic variance for yield under stress are actually accounting for the bulk of yield variation under stress that is not associated with variation in yield potential. In many populations, it therefore seems that genetic variation for yield under severe stress is under oligogenic rather than polygenic control. If confirmed, these results would indicate that large improvements in the performance of mega-varieties under drought stress may result from the marker-assisted introgression of a small number of genes.

Conclusions

Drought is a severe risk for rice producers who farm upper terraces with light soils, under both upland and lowland management, affecting productivity in both stress and favorable years, due to direct yield losses and underinvestment in inputs, respectively. Many widely grown varieties in rainfed rice-producing areas are highly susceptible to drought. More drought-tolerant cultivars are needed to replace them, but they are unlikely to be adopted if the quality and yield potential of current varieties are not maintained.

Several adaptations are required to increase productivity and reduce risk of crop loss due to drought on these lands, which comprise perhaps 20% of the rice area of Asia. These adaptations include increased ability to maintain vegetative biomass growth in intermittently dry soils, increased weed competitiveness, tolerance of delayed transplanting, and tolerance of severe drought stress at flowering. Specific adaptation to dry direct seeding in nonpuddled soils is also required for dry direct-seeding systems, which could allow farmers in drought-prone upper fields to establish their crops earlier to reduce the risk of drought during the critical flowering and grain-filling periods. The substantial genetic variation for all these traits can be exploited by rice breeding programs by incorporating screens for yield under appropriate timings and levels of drought stress for the target environment, and by incorporating screens for traits that are relevant to drought-prone rice systems, such as tolerance of delayed transplanting or dry direct seeding. High-yielding cultivars tolerant of lowland drought stress and delayed transplanting have been developed. Hybrids are particularly promising for drought-prone lowland fields because of their tolerance of moderate drying during vegetative growth and of delayed transplanting. Drought-tolerant cultivars adapted to direct seeding under nonpuddled aerobic conditions that combine yield potential of more than 5.0 t ha^{-1}, yields of at least 1.5 t ha^{-1} under severe stress, and a high amount of weed competitiveness have been developed by IRRI and collaborators. These cultivars are ready for evaluation as the basis for intensified management systems for drought-prone rainfed lowland rice environments. Further improvements in drought tolerance, particularly for lowland conditions, await better characterization of potential donors. Currently, IRRI is screening a large sample of lines from its core germplasm collection for tolerance of lowland stress; promising donors are being identified and will be made available to rice breeders.

In the future, marker-assisted backcrossing holds considerable promise for improving the drought tolerance of Asian rainfed mega-varieties. Genetic control over variation for yield under severe stress appears to be oligogenic, rather than polygenic, in many crosses. QTLs with large effects on yield under stress have been identified in several populations, and may not be infrequent in the rice germplasm. A major effort should be mounted to identify and characterize such genes for use in crop improvement.

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Notes

Authors' address: International Rice Research Institute, DAPO Box 7777, Metro Manila, Philippines.

Drought research at WARDA: current situation and prospects

M. Sié, K. Futakuchi, H. Gridley, S. Mande, B. Manneh, M.N. Ndjiondjop, A. Efisue, S.A. Ogunbayo, M. Moussa, H. Tsunematsu, and H. Samejima

Drought is one of the major constraints to rice production in the rainfed ecology in sub-Saharan Africa (SSA). It occurs not only in uplands but also in lowlands; for example, 70% of lowland rice farmers experience a drought problem at the reproductive stage, which can reduce yield more severely than at the vegetative stage. At WARDA, therefore, drought is one priority area to be addressed. In WARDA's interspecific breeding between *Oryza sativa* and *O. glaberrima* for the rainfed ecology, one of the most important characteristics is short duration to evade drought that often occurs in the latter days of the cropping season. Several interspecific lines (NERICA: New Rice for Africa) with growth duration of 90–100 days have been developed. Apart from this escape type, NERICAs showing better drought resistance than local *O. sativa* checks have also been identified. Several *O. glaberrima* landraces showing high resistance were identified after collection from the flood plains of the Niger River and crossing of these landraces with *O. sativa* and existing NERICAs with high agronomic performance has already been done. Several *O. sativa* varieties were also screened for drought resistance at both vegetative and reproductive phases. Promising *O. sativa* varieties with good drought resistance have been used in crosses with susceptible genotypes for creating breeding and mapping populations. The populations being created are expected to segregate for root characteristics and/or osmotic adjustment, both of which are important drought-resistance traits in rice. A WARDA-JIRCAS joint project also aims to develop drought-resistant varieties. The project narrowed target characters down to root penetration into the deeper soil layers, which is very effective for growth maintenance in certain drought situations. Highly promising *O. sativa* lines have already been identified, and the next step is to identify genes/QTLs for this trait for use in marker-assisted selection. Past drought research at WARDA mostly concentrated on varietal improvement. However, an agronomic approach is also within our purview. We inventory farmers' existing cultural practices to minimize the risks of yield reduction by drought and test their true usefulness. Integrated drought management options for rainfed rice combining resistant varieties and cultivation practices will also be developed and evaluated.

Rice has been cultivated in West and Central Africa for centuries and is now one of the region's staple foods. This is a unique crop adaptable to various ecologies ranging from free-draining upland soils to inundated and irrigated lowland soils. However, rice is more sensitive to water deficiency than other field crops such as cowpea and maize. Therefore, drought is one of the major constraints to rice production in rainfed environments (Cruz and O'Toole 1984). It occurs not only in uplands but also in lowlands; for example, 70% of lowland rice farmers experience a drought problem at the reproductive stage, which can reduce yield more severely than at the vegetative stage, according to a recent survey conducted at Sikasso, Mali, using the participatory rural appraisal (PRA) approach. Recently, in order to solve the problem, interspecific hybrids were developed by the Africa Rice Center by crossing *Oryza glaberrima* and *O. sativa* (WARDA 2000, Ishii 2003, Futakuchi et al 2003).

One of the most important characteristics of these interspecifics is short duration to evade drought that often occurs in the latter days of the cropping season. Several interspecifics (NERICA: New Rice for Africa) with growth duration of 90–100 days have been developed. As shown in the section on "Evaluation of breeding lines developed," NERICAs showing better drought resistance than local *O. sativa* checks have also been identified along with drought-escape types.

Lilley and Fukai (1994), Kobata et al (1996), and Fujii and Horie (2001) showed that high dry matter production by drought-resistant cultivars of rice (*O. sativa*) is caused by superior ability to gather soil water. Also, molecular tools have been used to facilitate the identification and genomic locations of genes controlling traits related to drought resistance (Lanceras et al 2004). Several researchers have reported genetic variation in rice for drought resistance. Several traits implicated in drought resistance of rice are deep rooting ability, osmotic adjustment, anther dehiscence, leaf rolling or nonrolling, recovery ability, early vigor, death of leaves, delay of heading, deformed rachids, and grain weight (Chang et al 1974). *O. sativa* indica varieties of rice are reported to have higher osmotic adjustment than *O. sativa* japonica varieties. On the other hand, japonica varieties generally have deeper root systems than indica varieties.

As new varieties are arguably a technology readily adopted by small farmers, the development of varieties combining improved drought resistance with good yield potential would help stabilize on-farm yield while increasing productivity and production. To develop such varieties requires the identification and transfer of genes from drought-resistant sources into high-yielding well-adapted varieties. QTLs associated with several important traits in drought resistance have already been identified; for example, osmotic adjustment (Zhang et al 1999, Robin et al 2003), relative water content (Babu et al 2003), canopy temperature (Babu et al 2003), flowering date (Lafitte et al 2004), maximum root length (Li et al 2005), deep root mass (Kamoshita et al 2002), root dry weight (Zhang et al 1999, Li et al 2005), root-pulling force (Zhang et al 1999), seedling vigor (Zhang et al 2005), and grain yield (Lanceras et al 2004, Bernier et al 2007).

In view of the importance of drought as a production constraint of rice in sub-Saharan Africa, it is be desirable to adopt an integrated approach to mitigate drought problems. However, the major component of the drought research at WARDA has been varietal development. Several special projects aiming to develop drought-resistant varieties, for example, a Rockefeller-funded project and a joint WARDA-JIRCAS project, have been implemented at WARDA. In this report, WARDA's drought-related activities are reviewed and future prospects are described.

Identification of genetic sources for drought resistance

To identify sources for the development of drought-resistant varieties, several field trials to screen *O. sativa*, *O. glaberrima*, and NERICA have been conducted.

Screening of *O. sativa*

This trial mostly focused on *O. sativa*, although some *O. glaberrima* and NERICAs were included in the entries. One hundred and twenty genotypes (Table 1) inclusive of *O. sativa* indica*,* *O. sativa* japonica*,* *O. glaberrima*, and NERICA (interspecific *O. sativa* × *O. glaberrima* progeny), which were sourced from WARDA, CIAT, and IRRI, were screened for drought resistance at the Togoudo research station (Benin) between 2005 and 2007. In this research, the drought screening protocol involved imposing a 21-day drought stress at 45 days after sowing (DAS), which coincides with the vegetative/reproductive phase of crop development. Two trials were conducted during the main dry season (Dec. 2005-March 2006 and Dec. 2006-March 2007) and one during the short dry season (July-August 2006). The trials were laid out in a split-plot design with irrigation regime (the plot of full irrigation throughout growth as a control and the drought treatment plot) as the main plot factor and genotype as the subplot factor. Within each subplot, the genotypes were randomized using an alpha lattice design. Data were collected following the standard evaluation system (SES) of IRRI (1996), in which applicable data collected were plant height, tiller number, leaf greenness rating (using a SPAD meter), leaf rolling, leaf drying, recovery ability, flowering date, leaf temperature, fresh and dry weights of organs before and after drought stress, number and length of leaves, number and weight of panicles, and grain yield per plant.

Over the two seasons of screening, grain yield under drought was found to be positively correlated with yield under continuous irrigation, implying that it is possible to breed drought-resistant rice genotypes with high yield potential.

Significant phenotypic correlations were detected between grain yield and several morphological and physiological traits (Table 2). Leaf greenness rating (SPAD reading), leaf width, and leaf length consistently had positive correlations with grain yield under drought conditions, whereas significant correlations were detected between grain yield and tiller number, days to 50% flowering, and leaf temperature, but the signs differed between the years. In 2005-06, grain yield was positively correlated with tiller number and leaf temperature and negatively correlated with days to 50% flowering, whereas grain yield in 2006-07 was negatively correlated with tiller number and leaf temperature and positively correlated with days to 50% flowering. It is noteworthy that all traits with significant correlations with grain yield under drought stress were only weakly correlated with grain yield (correlations below 50%). Hence, breeding

Table 1. One hundred and twenty lines and breeding lines used for drought screening at Cotonou.

No.	Line	No.	Line	No.	Line
1	Aliança	41	IR62266-42-6-2	81	RAM 134
2	Araure 4	42	IR64	82	RAM 152
3	B6144F-MR-6-0-0	43	IR74371-54-1-1	83	RAM 24
4	Bala	44	IRAT 104	84	RAM 3
5	Black Gora	45	IRAT 109	85	RAM 55
6	CAIAPO	46	IRAT 13 × OS6-AL-1CM-1JN	86	RAM 25
7	Carolino Blanco	47	IRAT 216	87	RHS 107-2-1-2TB-1JM
8	CG17	48	IRAT 13	88	RHS 107-2-2-1TB-1JM
9	CG14	49	ITA 186	89	Salumpikit
10	CG20	50	ITA 212	90	Short Grain
11	CO39	51	M 17	91	TGR 68
12	CT 6510-24-1-2	52	MGL 2	92	Tog5681
13	CT6946-6-2-2P-1X	53	Morobérékan	93	TOX 1011-4-1
14	CT7201-16-5P	54	NERICA 1	94	TOX 1012-12-3-1
15	CT7203-6-5P	55	NERICA 2	95	TOX 1177-17-16-8-1CH-2P
16	CT7415-6-5-2-2X	56	NERICA 3	96	TOX 1177-17-16-B-1CH-1P
17	CT7415-6-5-3-1X	57	NERICA 4	97	TOX 1779-3-3-201-1B
18	CT9993-5-10-1-M	58	NERICA 5	98	TOX 1840-3-2-3X
19	Dourado	59	NERICA 6	99	TOX 1857-3-2-201-1
20	Dourado Precoce	60	NERICA 7	100	TOX 1871-38-1
21	FONAIAP 2000	61	NERICA 8	101	TOX 718-AL-11-1CM-1JU
22	IAC 164	62	NERICA 9	102	TOX 718-AL-20-1CM-1JN
23	IAC 165	63	NERICA 10	103	TOX 718-AL-27-1CM-1JN
24	IAC 25	64	NERICA 11	104	TOX 891-212-2-102-2-101-1
25	IAC 47	65	NERICA 12	105	Vandana
26	ICC 004 Azucena	66	Ngovie	106	Vermelho Comun
27	ICC 124 Lac 23	67	OS6	107	WAB181-18
28	ICC 134 Kinandang Patong	68	P 5589-1-1-2P	108	WAB56-125
29	ICC 137 Ma Hae	69	P. Resistente Sequia	109	WAB96-1-1
30	ICC 208 Trembese	70	Paga Divida	110	WAB450-6-2-9-MB-HB
31	IDSA10	71	Palawan	111	WAB502-12-2-1
32	IDSA6	72	Perola	112	WAB56-104
33	IR55419-04	73	Pratao	113	WAB56-50
34	IR55423-01	74	Pratao Precoce	114	WAB56-57
35	IR58821-23-1-3-1	75	PSBRC 9	115	WAB638-1
36	IR71525-19-1-1	76	PSBRC 80	116	WAB706-35-K1-KB
37	IR74371-3-1-1	77	RAM 100	117	WAB880-1-38-19-26-P2-HB
38	IR78875-131-B-1-3	78	RAM 120	118	WAB96-1-1
39	IR78905-105-1-2-2	79	RAM 13	119	WAB96-3
40	IR52561-UBN-1-1-2	80	RAM 131	120	Zhen Shan 97

Table 2. Means of traits measured during and after 21 days of drought stress on a diverse population of rice genotypes under irrigated and drought-stressed conditions at Togoudo Research Station, Benin (n = 97) in 2005-06. Correlation of traits measured under stress with yield under stress is also included.

Trait[a]	Fully irrigated	Drought stress	Correlation with stress yield	S.E.D.
Height 64	90	75	0.05 n.s.	2.59
Tiller no. 60	19	12	0.163*	0.62
Tiller no. 92	22	19	0.170*	2.64
Leaf greenness 92	43.30	43.10	0.155*	0.52
Leaf no. 74	5	4	0.180*	0.39
Leaf length 74	42	34	0.128*	3.39
Leaf temp. 59	31	33	0.158*	0.22
Leaf drying 67	–	2.5	–0.153*	–
Leaf rolling 80	–	2.00	–0.157*	–
Leaf drying 80	–	1.70	–0.185**	–
Biomass 70 (g)	35.36	11.14	0.325**	–
Moisture content 70 (g)	107.13	31.09	0.220*	–
Biomass during stress	29.43	5.00	0.215*	–
50% flowering (days)	79	91	–0.196**	0.85
Fertile panicle no.	13	8	0.366**	1.26
Fertile panicle wt.	14.28	6.10	0.559**	2.30
Final biomass	62.26	49.49	0.212*	4.65
Grain yield per plant	12.35	5.03	–	2.31

[a] Numbers following trait names indicate the DAS on which the trait was measured.
** = significant at *P* <0.001; * = significant at P <0.05; n.s. = not significant.
S.E.D. = standard error of the difference between mean trait value under fully irrigated and under drought stress conditions.

for drought resistance should employ complex crosses aiming at pyramiding drought-resistance alleles in adapted backgrounds.

Screening of *O. glaberrima*

The main target of this screening was *O. glaberrima*, though some *O. sativa* lines were tested too. The genetic material in the study comprised 75 genotypes composing nine *O. sativa* lines, eight drought-resistant chromosome segment substitution lines (CSSL) from CIAT, and 58 *O. glaberrima* accessions that included the RAM series (Riz Africain du Mali) from the Institut d'Economie Rurale in Mali. The material was evaluated in three trials under two drought treatments consisting of 28 days of water stress initiated at 21 days (trial A) and 42 days (trial B) after sowing (DAS), with a third treatment, the control (trial C), with no water stress imposed. Each trial was laid out as an alpha lattice with three replicates and each plot had three plants. Soil water status in the water-stress treatments was measured in three 20-cm layers of soil from the surface to 60 cm. Data collected on individual plants were number of tillers, plant height, number and length of leaves, leaf rolling, seedling vigor, number and mass of panicles, and seed yield. The ultimate priority is the identification and development of genotypes with good yield potential under drought stress. The plots in the trials were too small to obtain a good estimate of the yield potential per hectare under drought stress. However, important yield components recorded—number of tillers and seed yield per plant—provide a good indicator.

A drought-stress effect was evident from 15 days after withholding water. The first plant response was leaf rolling and the RAM series of *O. glaberrima* accessions were the first to attain a leaf-rolling score of 9 and they remained in this state until resumption of watering. Other genotypes had the capacity to recover overnight, which was particularly marked for the two *O. glaberrima* accessions, CG14 and CG17. All phenotypic traits measured showed the effect of drought stress at 28 days following initiation of the stress at 21 DAS compared with those in the nonstressed trial. The same length of drought stress initiated at 42 DAS reduced aboveground biomass through leaf wilting and drying. Regardless of the timing of drought stress, the *O. glaberrima* accessions had better recovery ability than the *O. sativa* and CSSL lines, which may reflect the late tillering ability of *O. glaberrima* accessions, as this was not evident for the *O. sativa* cultivars and CSSL lines.

Forty-nine genotypes exhibiting good performance under drought stress were selected from the set of 75 described above to compare their root traits with those of Moroberekan, a well-studied drought-resistant *O. sativa* variety from West Africa.

WARDA-JIRCAS Drought Project

This project narrowed target characters down to root penetration into the deeper soil layers, which is very effective for growth maintenance in certain drought situations. The screening started in 2004 with 600 lines (*O. sativa* and *O. glaberrima*) in Bamako, Mali, in relation to the target trait. Evaluation of the promising lines identified continued in Ibadan, Nigeria, in 2005 and 2006 (Table 3). In the intensive screening, Khao Dam and Malagkit Pirurutong were identified as deep-root varieties and Ma Hae, Trembese, and Chau as shallow-root varieties. To identify QTLs associated with deep root, crosses were made between the deep- and shallow-root varieties and populations are being developed. In 2007, F_2 (Ma Hae × Khao Dam, Chau × Khao Dam) and F_3 (Ma Hae × Malagkit Pirurutong, Trembese × Malagkit Pirurutong, Chau × Malagkit Pirurutong) populations were available. Evaluation of populations in relation to root depth starts from the F_3 generation.

Generation of breeding and mapping populations

Interspecific BC_2F_2 populations derived from a top-cross

BC_1F_2 and BC_1F_4 interspecific progeny were developed from the crosses of CG14 (*O. glaberrima*) with elite *O. sativa* lines WAB56-104 and WAB638-1. These interspecific progeny were top-crossed to Morobérékan to develop three-way-cross BC_2F_1 populations from which individuals were genotyped with 51 microsatellite markers to assess

Table 3. Root depth of promising *O. sativa* entries identified at Ibadan.

Item	Ranking in root depth[a]	Accession	Root depth (cm)	Shoot dry weight (g)
Top 7	1 (4)	Malagkit Pirurutong	23.8 ± 6.4	34.2 ± 13.7
	2 (29)	Dam Ngo	22.8 ± 6.3	25.5 ± 8.3
	3 (58)	Godawee	22.7 ± 5.0	23.4 ± 9.5
	4 (54)	Dharial	22.0 ± 6.7	21.9 ± 8.6
	5 (87)	Arang	21.8 ± 9.4	35.7 ± 11.5
	6 (90)	DA 1	21.4 ± 9.4	35.7 ± 13.4
	7 (25)	Rathal	20.8 ± 4.5	32.1 ± 11.7
Average			21.2 ± 6.3	28.8 ± 12.0
O. glaberrima	41 (83)	TOG 5495	17.4 ± 3.6	29.1 ± 9.3
	49 (14)	TOG 5484	16.9 ± 3.3	28.5 ± 9.3
	56 (77)	TOG 5979	16.7 ± 3.1	34.1 ± 12.6
	68 (38)	TOG 5556	16.1 ± 4.6	25.4 ± 11.0
	75 (88)	TOG 5725	15.4 ± 5.0	29.3 ± 8.3
	94 (63)	TOG 6639	13.2 ± 3.4	23.2 ± 8.3
	98 (34)	TOG 5675	12.1 ± 3.1	32.5 ± 11.7
Average			15.4 ± 4.2	28.9 ± 10.5

[a] Numbers in parentheses are the rank in the screening at Bamako, Mali.

the contribution of the *O. glaberrima* accessions to their genetic makeup. Selfing of superior BC_2F_1 individuals generated nine BC_2F_2 populations for further selection.

About 10,000 BC_2F_2 individuals were screened for drought resistance by subjecting them to prolonged water stress of 35 days, starting from 42 DAS. Watering resumed at 77 DAS, allowing recovery. At maturity, selection based on growth duration, resistance to shattering, resistance to lodging, fertility, and drought resistance identified 3,000 individuals with the desired parameters for these traits.

One hundred twenty individuals with a short cycle (<100 days), representing 4% of the 3,000 individuals, were advanced to BC_2F_3, from which the following two sets of progeny are being developed:

- Seventy-four BC_2F_4 progeny from BC_2F_3 heterogeneous progeny selected for seedling vigor, high effective tiller number (weed competitiveness), panicle size, and grain number per panicle (>300 seeds per panicle).
- Fifty-four BC_2F_4 progeny from homogeneous BC_2F_3 progeny for yield evaluation in plots of 8 m^2.

The remaining 96% of the 3,000 BC_2F_2 individuals matured 100 to 125 DAS, and selection in heterogeneous BC_2F_3 progeny with confirmed drought resistance is based on tiller number, stay-green ability, appearance, and grain yield.

Breeding populations developed from *O. glaberrima* RAM accessions

To further exploit the drought resistance detected in the *O. glaberrima* RAM accessions, a series of crosses and backcrosses involving the drought-resistant RAM accessions and elite high-yielding but drought-susceptible *O. sativa* and interspecific lines have been undertaken. Forty-five crosses generated 531 BC_1F_1 seeds and BC_2F_1 populations are being developed for subsequent selfing, selection for drought-resistance and important agronomic traits, and distribution to NARES breeding programs. Additionally, to exploit and explore the *O. glaberrima* genome in greater detail than is possible in a backcross program, a large number of F_1 crosses between drought-resistant *O. glaberrima* RAM accessions and interspecific (*O. sativa* × *O. glaberrima*) lines were selfed. Although the intergenomic sterility barriers in crosses between *O. glaberrima* and *O. sativa* reduced the number of F_2 seeds to 5 or fewer in some crosses, 42 F_1 crosses yielded 155 F_2 seeds. The F_2 and subsequent generations provide an opportunity to develop a series of new interspecific recombinant progeny segregating for a wide range of genes/QTLs from the *O. glaberrima* genome.

Twelve BC_1F_1 and BC_2F_1 populations, developed from crosses between drought-resistant *O. sativa* lines and elite high-yielding but drought-susceptible *O. sativa* and from interspecific (*O. sativa* × *O. glaberrima*) crosses are being selfed to quickly develop a range of progeny to screen for drought resistance and yield.

Generation of mapping populations

IR64 and ITA212, lowland drought-susceptible lines, are being crossed, respectively, with 18 and 17 drought-resistant donor lines to develop mapping populations. Recombinant inbred lines and doubled haploids will be developed from the progeny derived from these crosses and will be used in mapping QTLs for drought resistance.

Additionally, drought-resistant upland lines NERICA 1 to 7, WAB56-104, IAC 165, and WAB96-3 are involved in 55 crosses with sources of drought-resistance traits to develop breeding populations for selection.

As a specific aspect of the project is to exploit the drought resistance detected in the *O. glaberrima* RAM accessions from Mali, CSSL populations are being developed from crosses of 18 accessions of *O. glaberrima* RAM accessions with two *O. sativa* varieties, namely, Morobérékan and WABC165. Twenty-two cross combinations generated the F_1 generation, and BC_1 and BC_2 populations are being developed.

Evaluation of breeding lines developed

Upland lines developed have been routinely subjected to evaluation for drought resistance. When the WARDA research station was in M'bé, Côte d'Ivoire, before the Ivorian crisis, some of the lines were tested in relation to their response to various soil water conditions using a sprinkler method. As an example, data from a trial in the dry season of 2000-01 are reported.

Three rows of sprinklers were installed in an upland rice field at an interval of 15 m and rice plots in four replicates were established between them. The plots were irrigated for 2 hours daily for 3 weeks from seeding, after which only the central row of sprinklers was operated. The trial was conducted for two seasons with the same varietal entries. It was expected that the amount of irrigated water would become smaller with the distance from the central row of sprinklers. Thus, five treatments of soil water conditions were used: 0–3 m (1st plot); 3–6 m (2nd plot); 6–9 m (3rd plot);

Table 4. Yield of NERICA lines and check varieties in various soil moisture conditions (2000-01).

Line/variety	Yield (t ha^{-1})				
	1st plot[a]	2nd plot	3rd plot	4th plot	5th plot
CG 14	2.34	1.68	2.33	0.62	0.04
WAB56-104	1.87	1.18	1.75	1.29	0.08
Bouaké 189	1.43	0.70	1.57	0.62	0.00
WAB450-24-3-2-P18-HB	2.06	1.29	1.97	0.83	0.27
Moroberekan	1.86	0.78	1.45	0.58	0.10
45 NERICA lines					
Mean	2.23	1.56	2.02	1.00	0.05
S.E.	0.52	0.30	0.44	0.22	0.08
Min.	1.04	1.01	1.06	0.43	0.00
Max.	3.08	2.24	3.17	1.51	0.55
LSD (5%)	0.96	0.83	1.14	0.78	0.25

[a]The distance of each plot, from 1st to 5th, was increasing from the central sprinkler row.

9–12 m (4th plot); and 12–15 m (5th plot) for the distances from the central row of sprinklers. Forty-five upland NERICA lines (WAB878, WAB880, and WAB881 series) of the second generation were tested with the following five check varieties: Moroberekan (a tolerant check, a traditional *O. sativa* japonica variety); WAB56-104 (an improved *O. sativa* japonica variety); Bouaké 189 (a susceptible check, an improved *O. sativa* indica variety); CG14 (*O. glaberrima*); and WAB450-24-3-2-P18-HB (one of the first-generation NERICA lines).

On average, the new-generation NERICA outyielded the resistant check, Morobérékan, in all water treatments other than the severest drought plot (the 5th plot) (Table 4). In the 5th plot, however, one NERICA line, WAB878-6-37-8-1-P1-HB, significantly outyielded (0.55 t ha^{-1}) all the check varieties. The yield of this new NERICA line was 1.63, 1.48, 2.45, 1.36, and 0.55 t ha^{-1} in the 1st, 2nd, 3rd, 4th, and 5th plots, respectively. This line produced a comparatively high yield (1.36 t ha^{-1}) in the 4th plot and is promising for drought-prone upland conditions.

The prime cause of yield reduction in the soil-water-deficit plots was the occurrence of a large number of unfilled grains in these conditions. The percentage ratio of the ripened grain of WAB878-6-37-8-1-P1-HB was 85.5%, 86.3%, 85.0%, 51.8%, and 16.9% in the 1st, 2nd, 3rd, 4th, and 5th plots, respectively. This line and two check varieties, WAB450-24-3-2-P18-HB and Morobérékan, had significantly higher ratios than 0 in the 5th plot with severe soil water deficit (Table 5).

Conclusions and prospects

Several *O. glaberrima* landraces showing high resistance were identified and crossed with *O. sativa* and NERICA lines with high agronomic performance. Several *O. sativa* varieties were also screened for drought resistance in both vegetative and reproductive

Table 5. Percentage ratio of filled grains in NERICA lines and check varieties in various soil moisture conditions (2000-01).

Line/variety	Ratio of filled grains (%)				
	1st plot[a]	2nd plot	3rd plot	4th plot	5th plot
CG 14	78.6	76.8	77.7	26.7	1.8
WAB56-104	82.1	78.2	80.3	52.9	3.2
Bouaké 189	38.4	18.5	51.4	16.0	0.0
WAB450-24-3-2-P18-HB	65.8	72.0	81.7	46.8	20.4
Moroberekan	68.2	60.4	70.9	44.8	15.6
45 NERICA lines					
Mean	78.9	75.9	78.7	45.7	2.8
S.E.	4.6	5.2	6.9	9.7	2.9
Min.	66.6	63.1	53.2	24.6	0.0
Max.	85.5	86.3	86.5	62.7	16.9
LSD (5%)	12.6	14.8	16.9	32.2	11.8

[a] The distance of each plot, from 1st to 5th, was increasing from the central sprinkler row.

phases. Promising *O. sativa* varieties with good drought resistance have been used in crosses with susceptible genotypes for creating breeding and mapping populations. The populations being created are expected to segregate for root characteristics and osmotic adjustment, both of which are important drought-resistance traits in rice.

WARDA's *O. glaberrima* collection has not been fully explored for drought resistance. Evaluation and screening will continue. However, sources of drought resistance will not be restricted to *O. glaberrima* and will be expanded to *O. sativa* and other wild relatives such as *O. barthii*.

QTL identification is also ongoing for some characteristics associated with drought resistance; for example, deep root is focused on in a WARDA-JIRCAS joint project at Ibadan, Nigeria.

Meanwhile, varietal improvement is a major approach at WARDA to address drought problems, and an agronomic approach is also within our purview. We will inventory farmers' existing cultural practices to minimize the risks of yield reduction by drought and test their true usefulness. Integrated drought management options for the rainfed rice ecology by combining resistant varieties and cultivation practices will also be developed and evaluated.

Geographic information systems need to focus on the methodology for assessing drought risk: the patterns of drought profile for rainfed rice and impacts of climate change on drought occurrence for rainfed rice. The historical climate data analysis of drought patterns needs to focus on the interannual variability of rainfall (start, end, length of the season), the profile of dry spells, the probability of occurrence, the water balance, and crop risk failure because of drought.

Drought profiling will be analyzed with spatial indicators using optical and thermal indicators such as normalized difference vegetation index (NDVI), land surface temperature (LST), and vegetation temperature condition index (VTCI). There are anomalous images showing areas where production deviates from long-term, average production (Fig. 1A and B).

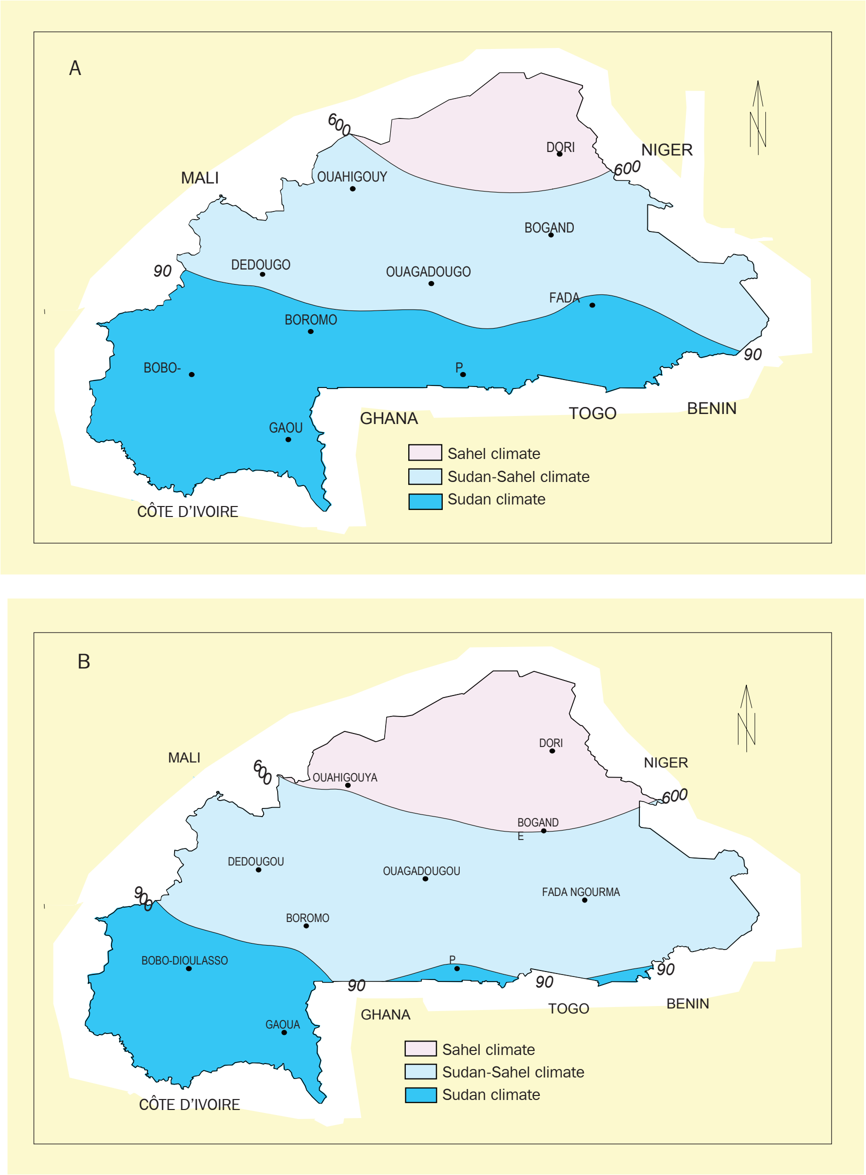

Fig. 1. Burkina Faso climatic zones, (A) 1951-80 and (B) 1971-2000.

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Notes

Authors' address: Africa Rice Center (WARDA), 01 B.P. 2031, Cotonou, Benin. Tel.: (229) 21 35 01 88; fax: (229) 21 35 05 56; email: m.sie@cgiar.org.