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O'Toole,J.C.; Chang,T.T.

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DROUGHT AND RICE IMPROVEMENT IN PERSPECTIVE[1]

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[1]by J. C. O'Toole, associate agronomist, Agronomy Department, and T. T. Chang, geneticist, Plant Breeding Department, The International Rice Research Institute, Los Baños, Laguna. Paper presented at the International Conference on Stress Physiology of Plants Useful for Food Production, 28-30 June, 1977, Boyce Thompson Institute, Yonkers, New York. Revised and submitted to the IRRI Research Paper Series Committee, 28 December 1977.

DROUGHT AND RICE IMPROVEMENT IN PERSPECTIVE

The importance of incorporating higher levels of drought resistance into the major food cereals on which man increasingly depends needs no justification. The physiological and genetical aspects of crop improvement relative to drought have been extensively studied for wheat, corn, and sorghum. The improvement of rice, however, has been ignored, partly because of the contrasts in governmental and institutional levels of agricultural research betweem most rice-growing countries and those which grow the other cereals as major crops. Just as important, perhaps, may be the misconception that the yield of rice, a semiaquatic species grown primarily in tropical regions of monsoon Asia, is virtually safe from, or not limited by, water deficits.

Whatever the cause of this disparity of research, drought in rice is a real concern and a serious yield-limiting factor on much of the world's 70 million hectares of nonirrigated rice.

To put drought and the extremely diverse conditions in which rainfed rice is grown into a clearer perspective, the physiological basis for drought resistance in the rice germ plasm is examined and recent efforts in selection and breeding for drought resistance are discussed. This paper attempts to stimulate a greater appreciation for drought resistance in rainfed rice, to illustrate the adaptive mechanisms available in the germ plasm, and to encourage more research on the soil-plant-water relationships of the rice crop.

Definition and terminology

The literature on agricultural drought often lacks concise definitive information. The particular interests and backgrounds of those studying drought have determined the approaches taken, which are reflected in the numerous definitions and criteria used across various disciplines. Most often, lack of rainfall and the resultant soil-moisture deficit form the basis of definition.

A general survey of definitions of drought, such as that reported in the World Meteorological Organization's (WMO) Technical Note No. 138 (1975), lists the variables that have been used, either alone or in combinations, to develop working definitions of drought. The WMO publication presents an excellent summary of drought definitions or associated concepts. Among the definitions included, 14 are based on rainfall, 13 on rainfall and mean temperature, 15 on soil-water and crop parameters, and 11 on climatic indices and estimates of evapotranspiration. Rainfall, air temperature and humidity, evaporation from free water, transpiration from plants, soil moisture, wind, stream flow, and plant condition are among the prominent criteria used.

Obviously rainfall is the primary single factor influencing the incidence of drought in the macroclimatic sense.

The vast majority of the world's rice lands are located at tropical latitudes (<25°) and in regions characterized by monsoon rainfall patterns (Huke, 1977). Those regions often have high annual rainfall totals, which connote an adequate water supply.

Two of the principal climatic characteristics of these regions offset an apparent water adequacy. First, the rainfall totals are often products of a series of high-intensity rainfall events which cause loss of excessive amounts of water to surface runoff or deep percolation. Thus the high rainfall totals are deceptive and often mask the real problem, which is one of rainfall distribution. Second, the same regions have potentially high solar radiation intensities and concurrent atmospheric evaporative demand during rainless periods (Sastry, 1976). Rainfall distribution and high evaporative demand call for a reassessment of high rainfall totals as grounds for assuming an adequate water supply for rainfed rice culture.

Despite these problems, rainfall distribution is the best and often the only available indicator for delineating drought-prone seasons or areas, although it has limitations because the water status of a rice field or crop is also a strong function of its physiographic location. The more sophisticated definitions, based on soil and plant water status, have yet to be tested on the rice crop.

This brief overview of the terminology, definitions, and concepts associated with the nebulous term "drought" is meant to encourage a careful diagnosis of the problem as a first step in approaching crop improvement against this location-specific environmental stress.

Ecological diversity of rainfed rice cultural systems

Before a discussion of drought resistance in rainfed rice, an appreciation of the ecological diversity to which rice has adapted is imperative.

Rice, perhaps more than any other crop, has been so intensively exposed to adaptive pressures and selected by man's efforts to expand its range that it now occupies an ecological continuum for which there is no in-depth description. Our purpose is not to remedy this shortcoming of rice literature. But with Figures 1 and 2, which illustrate the hydrologic, physiographic, and climatic variability of the world's rice lands, we present a brief treatment of how these and other primary environmental factors (Table 1) interact to provide a complex array of rice-growing environments.[1/]

When the world's rice cultural systems are viewed macroscopically (Fig. 1) the common denominator across them is the hydrological regime. That is

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[1/] For further elaboration on the evolutionary dynamics of cultivars adapted to rainfed cultures, see Chang (1976a, b, c).

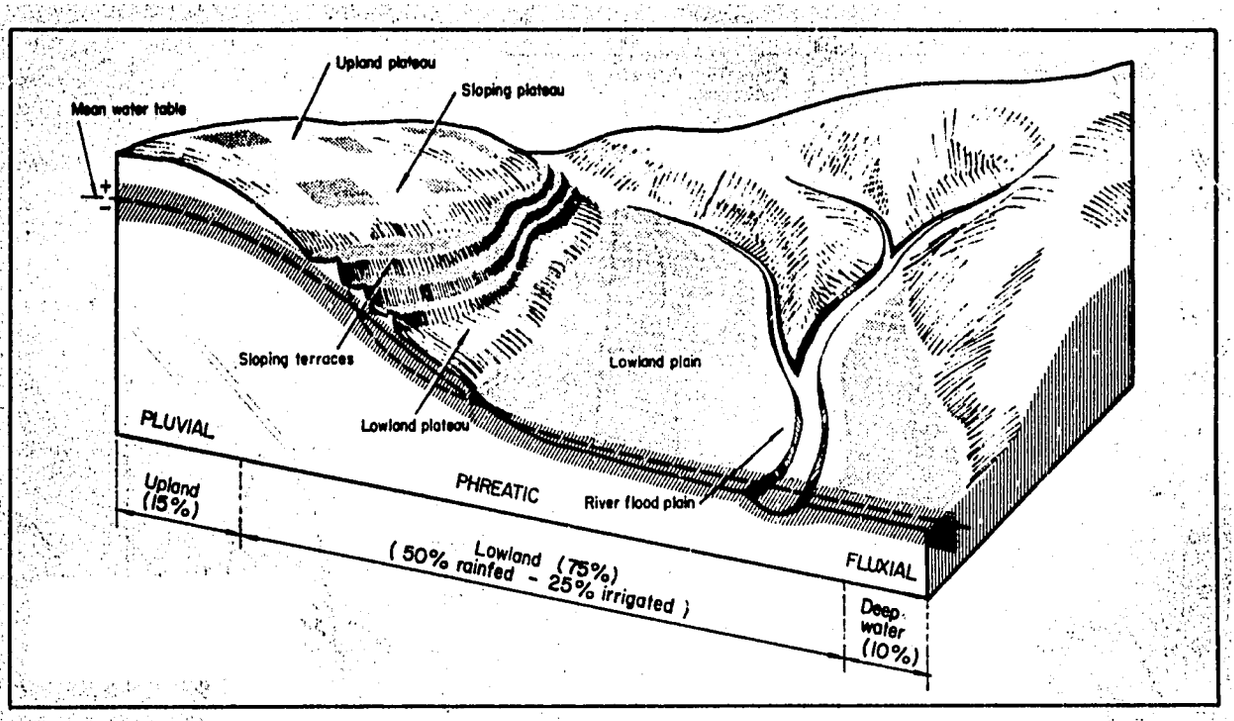


Fig. 1. Overview of the world's physiographically and hydrologically diverse rice cultural systems. Upland and deep-water areas illustrate the extremes of the spectrum but the vast majority of rice grows in lowlands where water conditions during the monsoon preclude culture of any other cereal. As much as 70 percent of the world's rice is rainfed. These diverse systems are classified by the predominant hydrological feature of the crop environment; pluvial, phreatic, and fluxial (terminology from Moorman and van Breemen, 1978).

further amplified when the scope of species adaptation is placed in hydrological perspective (Fig. 3). The continuum of hydrological regimes in which rice is grown offers such diversity that only a scalar type of classification such as depicted in Figures 1 and 3 is appropriate. For discussion purposes, the three major cultural systems -- upland, lowland, and deep water -- have been separated as if representing distinct, disjunct entities (Table 1). Note, however, that an attempt to extrapolate the characteristics of these finite divisions directly to field conditions will often result in error.

Briefly, upland sites are characterized by an aerobic soil in which no attempt is made to impound water.[2/] Lowland rice sites are characterized by low bunds or dikes dissecting a landscape, which may have been altered by land-forming practices to enhance water catchment and direct flow. Intensive wet cultivation to incorporate water into the soil is preferably followed by continual submersion until shortly before harvest.

Water depth in lowland rainfed rice fields usually is not a static factor. It shows great latitude in both temporal and spatial parameters across

[2/] For a more detailed description of the major upland rice environments, see IRRI (1975b).

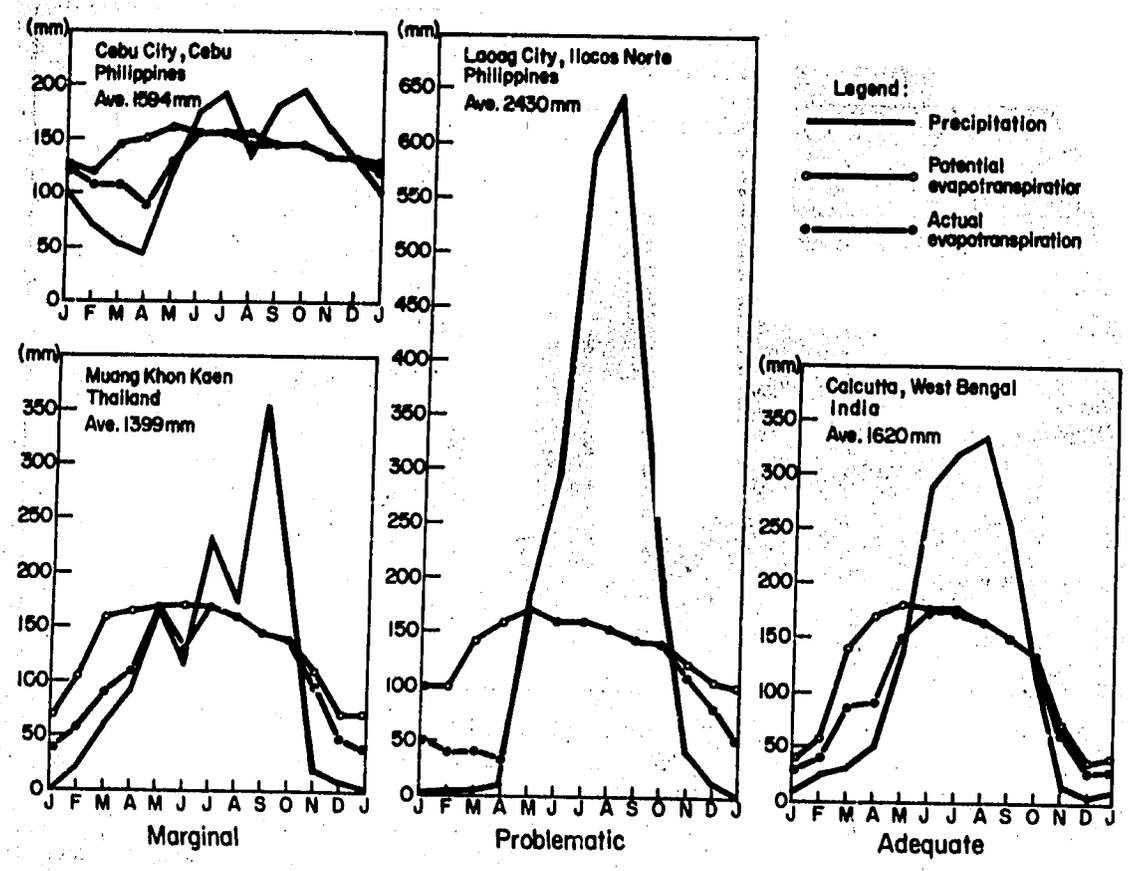


Fig. 2. Three climate patterns representing marginal, problematic and adequate rainfall types for rainfed rice. Marginal - continuous periods of adequate rainfall are not long enough to complete all crop growth stages without drought; problematic - period of rainfall is just long enough but rapid onset and ending of the monsoon often cause characteristic drought damage; adequate - period is long enough with good distribution at beginning and end allowing some flexibility in farmers' timing of essential operations (Adapted from Thornthwaite and Associates, 1963).

the vast low-lying regions of tropical Asia. Thus the distinction between intermediate and deep water is poor. The deep-water rice areas of Bangladesh and Thailand represent a unique hydrological situation within rice systems. The crop is commonly dry-sown on land cultivated either wet or dry. After a period of 4 to 6 weeks, during which the crop establishment is dependent on rainfall, as much as 6 meters of water from adjacent water sheds accumulates. As with lowland rice-growing systems, crop maturity and harvest periods are timed to coincide with the recession of flood waters. A more specific definition of upland, lowland, and deep water rice-growing systems would be self-defeating.3/

3/ Unfortunately, a comprehensive review of tropical lowland and deep water rice environments is not available. The following deal with the major environmental factors pertinent to our discussion: IRRI, 1975b, 1976b (climate); Grant, 1965 and Ponnamperuma, 1972 (soil); and Moorman and van Breemen, 1978 (hydrology).

Table 1. Generalized description of environmental factors[a] potentially interacting (directly and indirectly) with a rainfall deficit condition to create an array of complexes collectively referred to as "drought." The factors are considered in relation to their variability across location and through time and to the principal cultural systems in which rainfed rice is grown.[b]

Variability[c] and factor	Characteristics of cultural system		
	Upland	Lowland	Deep-water
● Edaphic			
Physical			
* Depth (potential root zone)	Often deep	Averaging 10 to 30 cm	Usually deep
* Texture	Light (sandy to clay loam)	Heavy (clays – few loams)	Heavy (clays)
* Physical obstruction (plow or hard pan)	Uncommon	Present	Absent
*† Hydraulic conductivity	High	Low	Low
Chemical			
*††‡Biochemical	Aerobic	Anaerobic (possibly alternately aerobic)	Aerobic → Anaerobic
*††‡Deficiencies or toxicities, e.g.,			
Fe deficiency	Yes	No	No
Zn deficiency	No	Yes	Yes
Al toxicity	Yes (at pH < 5.0)	No	No
* Native fertility	Low	Wide Range	High
● Climatic			
*††‡Rainfall			
Totals (crop season)	500 to 1500 mm	700 to 2000 mm	Not relevant – influx is from surface flow
Distribution (crop season)	3–4 months > 200 mm	3–7 months > 200 mm	Deficits in early stage associated with erratic onset of monsoon
*††‡Temperature			
Air	Variable by geographic location – longitude, latitude, elevation and hydrological conditions		
Soil			
*††‡Atmospheric evaporative demand	Determined primarily by macroclimatic conditions but respond significantly to microclimatic modifiers		
*††‡Wind			
*††‡Solar radiation (crop season)	Generalization on quantity or photoperiod not possible		
● Hydrologic			
*††‡Water depth			
(surface)	Rarely > 0	0 to 100 cm	1 to 6 meters
(subsurface)	Low	High (often perched)	Become positive
*††‡Occurrence of water excess (flood)	Rare	Rare to annual flooding	Annually
● Biotic			
*††‡Competitive plants (weeds)	Severe	May be severe	Severe during establishment
	Drought accentuates the problem in all systems		
● Agronomic			
*† Land preparation	Dry	Wet	Dry
*† Crop establishment	Direct sown (dry)	Direct sown or transplanted (wet)	Direct sown (dry)
*† Use of agrochemicals	Negligible	Wide range related to water control	Negligible

[a]The authors have not attempted an indepth survey of environmental factors affecting rainfed rice growth, development and yield but have concentrated on illustrating the large number of salient factors and attendant variability of each which may significantly interact (directly or indirectly) with rainfall deficit and thus modify the location specific phenomena collectively termed "drought."
[b]Hydrology and physiography of rice cultural systems are also illustrated in Figure 2.
[c]* = variable across locations; † = variable across seasons; ‡ = variable within seasons.

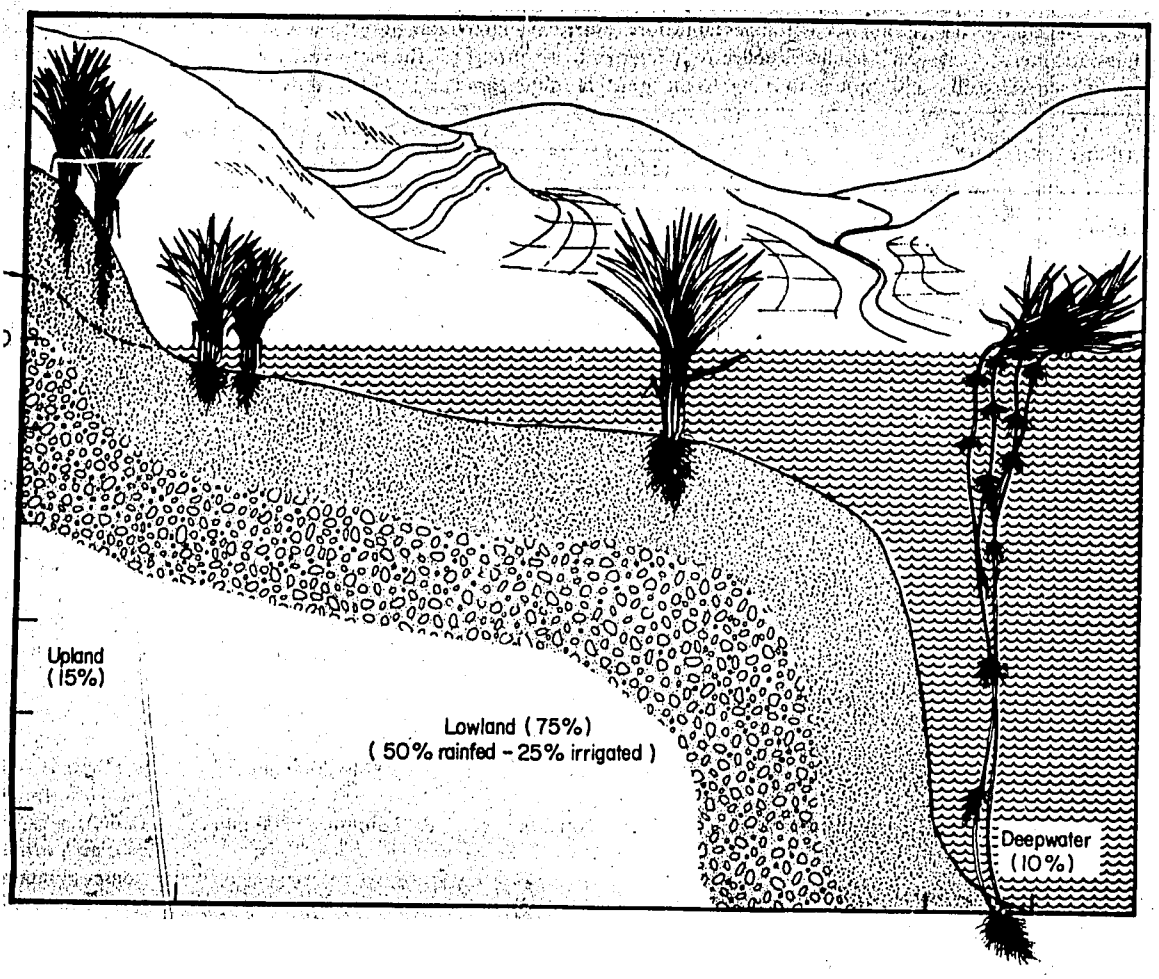


Fig. 3. Cross section of rice habitats illustrate the hydrological spectrum to which rice has been adapted and the resultant diversity of plant types (adapted from IRRI, 1975a).

Figures 1 and 3 and the preceding discussion make a strong connection between physiographic and hydrologic conditions. Also, the climatic information (Fig. 2) encourages the conclusion that upland rice areas are "drier" and lowland areas are "wetter" in terms of climatic conditions Both these assumptions, if applied generally, may be useful. But within a given rainfall zone, physiographic differences may cause a large spectrum of cultural systems not predictable by climatic inference. Table 1 requires more discussion on how the principal environmental factors may directly or indirectly interact to modify or contribute to the location specificity of "drought."

Although it is a simplified idea of the complexity characterizing rice crop ecology, Table 1 has many features that are not ordinarily associated with a discussion of drought resistance. Some points indicate possible interactions between the direct effect of drought on crop water status and the indirect effects via other physical and chemical parameters of the rice environment. The dynamic nature of chemical changes in rice

soils is a good example. In Table 1, the basic difference in oxidation-reduction conditions between upland and lowland soil chemical systems is perhaps secondary to the changed soil redox conditions in lowland paddies during drought. Lowland soils that undergo drying, and consequently become aerobic, undoubtedly affect the crop's performance through changes in nutrient availability. This condition should not be confused with the nutritional problems commonly associated with drought in which the aqueous pathway of ionic movement is disrupted. The redox potential of a previously saturated soil can change at soil moisture tensions of only ≈ -0.1-0.2 bar (Patrick and Fontenot, 1976). Changes in redox potential alter the availability of phosphorus and silicon and affect the concentration of Fe^{++}, Mn^{++}, and SO_4^{--} directly, as well as that of Ca^{++}, Mg^{++}, Zn^{++}, and MO_4^{--} indirectly (Ponnamperuma, 1977).

The relationships between soil redox potential, soil moisture level, and the consequences on crop physiology will vary with soil type. Undoubtedly these factors will continue to interact to bias results of tests designed to select varieties for response to soil-moisture deficits (IRRI, 1974) and add yet another significant but rarely monitored variable influencing location specificity of drought resistance in rice.

The indirect effects of flooding or of excess water depth may also appear unrelated to drought resistance. However, the pretreatment of the crop and the relative frequency with which flood and drought occur are relevant. In a later section, we will be concerned with the adaptation or adjustment of the crop to a progressive water deficit condition. Thus the conditioning or pretreatment by flood conditions or by cycles of water excess and deficit will affect the "state" in which a crop enters into a succeeding drought. These uncontrolled water conditions have produced rather paradoxical requirements for rice culture in much of lowland Asia. The inability to cope with water deficits and excesses, often in succession, has been noted as a shortcoming of the first-generation high yielding varieties produced in the 1960's. The incorporation of a similar flexibility, which allows traditional cultivars to survive such extremes, is currently one of the major objectives of IRRI's genetic evaluation and utilization (GEU) program.

Regardless of the hydrological or cultural system, rices have been naturally and artificially selected for their competitive ability with indigenous weed species.

In upland conditions, a major constraint to increased rice production is weed competition. Reports from Asia and Africa illustrate how poorly adapted rice is for competition with upland weed species (De Datta et al., 1976).

The capability to occupy a hydrophytic niche has protected lowland rice from competition with the more noxious forms of upland species. Weed control ranks high as an attribute of good water management.

When a water deficit occurs in either upland or lowland fields, the competitive advantage appears to shift toward the weed species.

Our preliminary observations indicate that weed species maintain a higher

leaf water potential and water use, as indicated by their continued growth and development. Initially, the better adapted weed species continue to grow and develop relatively unperturbed while rice shows impaired growth and development. Thus weed species, by using water potentially available to the crop, accentuate and hasten the depletion of stored soil moisture. Such depletion might be considered a direct effect related to the crop water status. For the farmer, however, the most obvious result is the accentuated weed problem and cost of weeding. Depending on the rice crop's growth stage and the skill of the farmer, the flush of weed growth may go unheeded. The net result, lower yield, is attributed solely to the greater weed population, which at later stages is more visible than the drought that induced it.

Agronomic practices undoubtedly play a major role in determining the onset, rate of progression, intensity, and duration of drought. Plant spacing alone would alter all of these parameters of drought if the decrease in ratio of actual to potential evapotranspiration of the crop were the criterion. Land preparation or land forming, and fertility level, whose effects have been documented in other cereal crops, have not been evaluated for their effects on rice-water relations during drought. Very little is known about how cultural practices may ameliorate the effects of drought in rice. But it is expected that upland rice would respond to water-conserving practices even without the advent of below-normal rainfall. Besides the modification of the soil's water-holding capacity by "puddling" and the building of dikes to impound water, cultural practices in traditional rice systems have not been studied from this point of view. Other moisture-conservation practices appear feasible and deserve consideration where applicable.[4/]

DROUGHT RESISTANCE ADAPTIVE MECHANISMS AND THEIR IDENTIFICATION

The diversity of rice-growing environments and the resulting traditional plant types adapted to them support the contention that the rice germ plasm contains numerous adaptive mechanisms that enable the crop to cope with water deficits.

Several adaptive mechanisms in the rice germ plasm may be exploited to enhance the crop's capability to establish, grow, develop, and yield during drought.

The applicability of each type of mechanism, however, must be placed in proper ecological perspective and should not be accepted as a drought resistance trait per se. Evidently, because of the extreme ecological diversity of rice cultural systems, adaptive mechanisms suited to a particular set of drought conditions may have little or no relevance in an ecologically dissimilar background.

[4/] Even a brief treatment of agronomy for drought-prone regions is beyond the scope of this paper, although the fundamental theory underlying these practices appears applicable to rice in many rainfed situations.

Because some ambiguities and controversies have arisen from terminologies of various authorities and because the rice crop is unique, we skip an extensive discussion based on previous definitions and instead consider the adaptive mechanisms of rice chronologically, as if drought were progressing through time.

Virtually every paper or review concerning the physiology of drought resistance begins with an acknowledgement of different types of mechanisms or adaptations. The simplest, most common, and generally accepted classification is

Drought resistance = drought avoidance + drought tolerance

althought Levitt et al. (1960) and Levitt (1972) have greatly amplified and subdivided this simple scheme.

Escape mechanisms

Before considering adaptive mechanisms for avoiding or tolerating drought, we should consider drought escape, the most effective adaptive mechanism where productivity is concerned.

Drought escape, selected for in all rainfed rice systems, aims to completel preclude drought from interacting with crop growth and yield.

One method of selecting for drought escape uses cultivars whose sensitive reproductive stages are photoperiodically controlled to coincide with the peak monsoon season, allowing the crop to complete grain filling with adequate water (Fig. 4). In locations where rainfall distribution is bimodal or where the monsoon ends sharply, photoperiod sensitivity appears to be a key attribute of local varieties. Several authors have indicated the value of photoperiod sensitivity as an adaptation for coping with problems of rainfall deficiency or distribution (Oka, 1958; Vergara and Chang, 1976).

Another method has been used in areas where rainfall patterns are marginal for rice production. It selects for short-duration varieties whose life cycle fits into the available, although short, time when rainfall is assured (Fig. 4).

Krishnamurthy et al. (1971) used this feature almost exclusively in describing a systematic approach to varietal selection for India's drought-prone regions.

Avoidance mechanisms

As a rainless period progresses the crop's first defensive reaction is to avoid internal stress by initially taking up stored soil moisture to meet evaporative demand. Later, as the soil-water potential at the root-soil interface becomes limiting, the defense may involve control of water loss to the atmosphere as well. Figure 5 illustrates some root and shoot characteristics that enhance uptake and conservation of water during a rainless period.

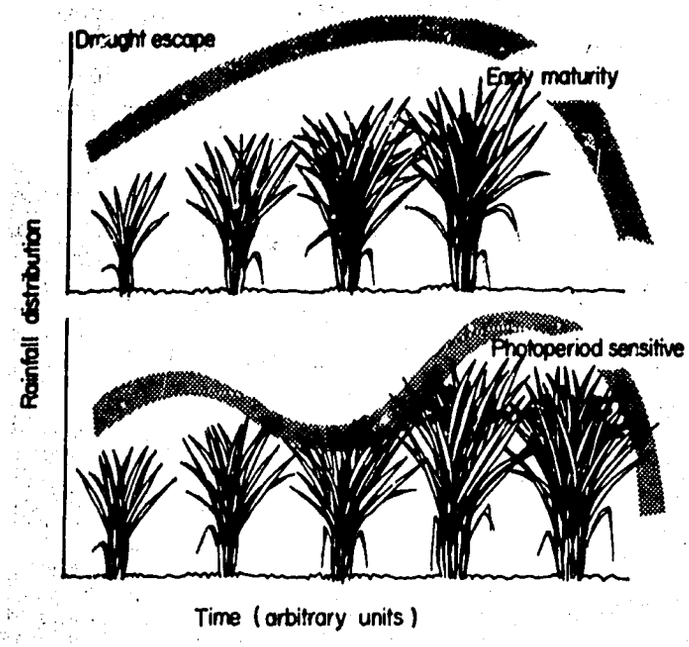


Fig. 4. Drought escape mechanisms - plant characteristics that allow the rice crop to carry out the yield-determining growth stages during periods of adequate moisture.

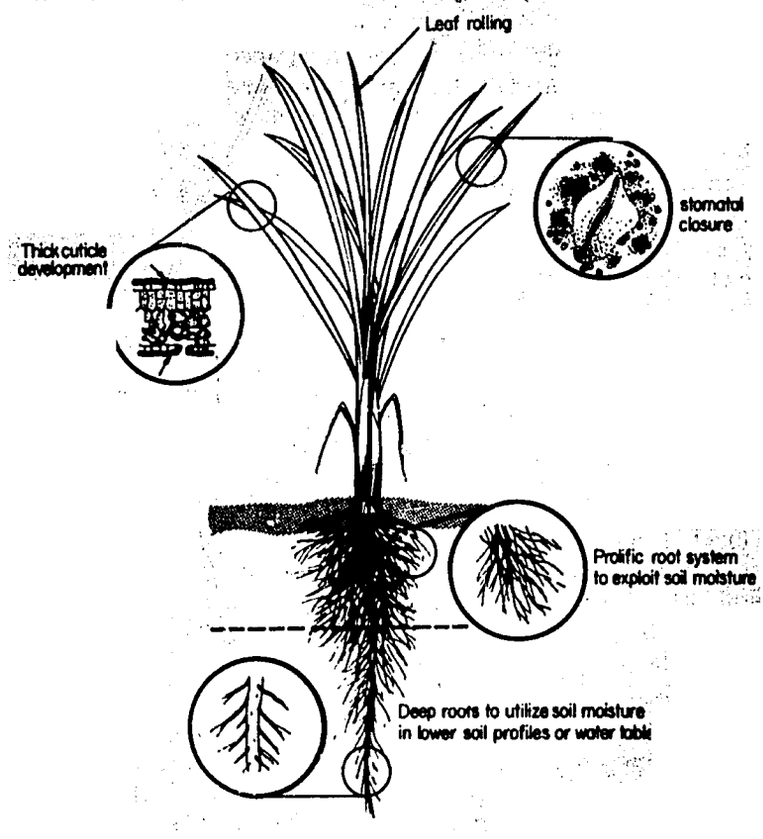


Fig. 5. Drought avoidance mechanisms - plant characteristics that prevent severe water deficits or prevent long duration of water stress.

Adaptive mechanisms that enable a crop to maintain water uptake would be combinations of a denser (greater root-soil interface per cubic centimeter of soil) and deeper rooting habit. The combinations selected for at a particular site will be determined by the soil's physical properties, such as depth and hydraulic conductivity of the soil. Chang and Vergara (1975) reviewed early work on root systems as an approach to drought resistance for upland rice, a subject that has received the increased attention of researchers in recent years.

More recent studies at the IRRI (1975a, 1976a, 1977) and at the Institut de Recherches Agronomiques Tropicales et des Cultures Vivrieres (IRAT), Bouaké, Ivory Coast (Reyniers and Binh, 1977), continue to illustrate the importance of root-system adaptations to the overall drought resistance of upland rices in Asia and Africa. They emphasize depth of rooting and root-to-shoot ratio. Figure 6 compares the vertical rooting distribution of several rices with that of wheat, corn, and sorghum. The relationship of the deep rooting characteristic with upland-field drought-screening scores is well illustrated by Figure 7. As the ratio of the deep root to the shoot increased, the visually scored field drought resistance increased. The visual scoring was based on the criteria of Chang et al. (1974).

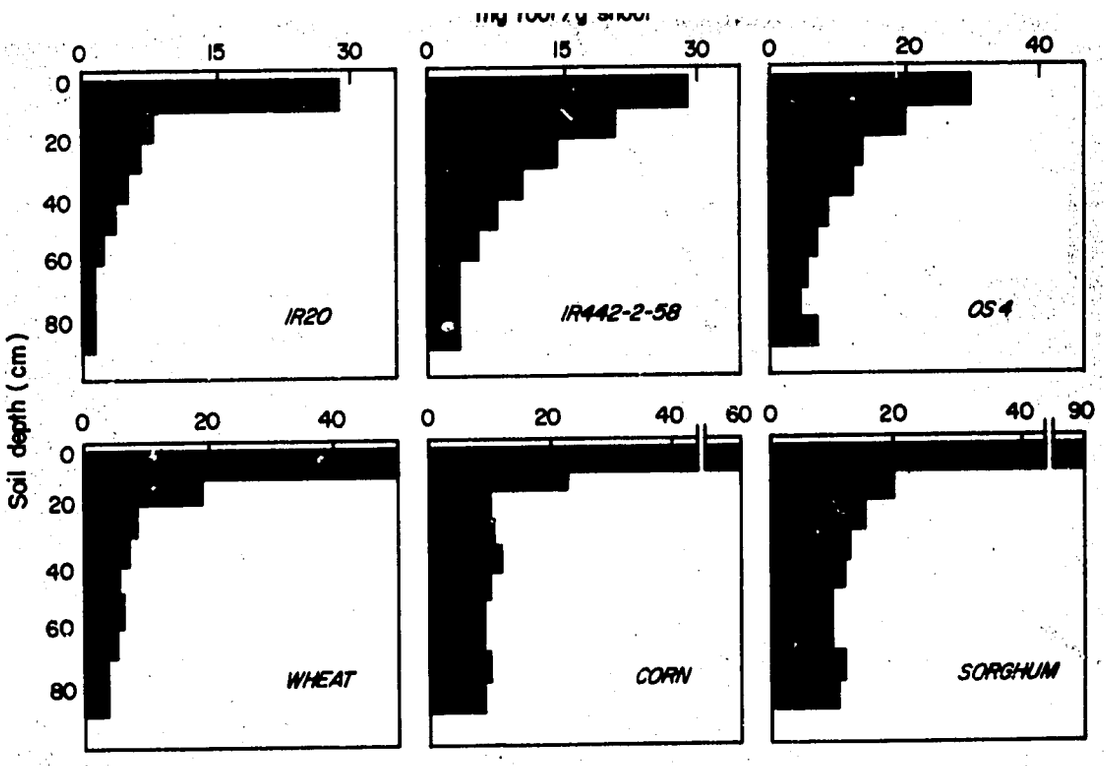


Fig. 6. Distribution of depth of root dry weight per gram of shoot dry weight (mg root/g shoot) of three rice varieties, wheat, corn and sorghum. (IRRI, 1975a).

Selection for root characteristics is problematic, however. To date techniques for direct field observation of roots have proved too laborious for use in a breeding and selection program. Observations of root system development, such as those described by Hurd (1968) or those used at IRRI (1975a) allow a cursory evaluation of the germ plasm but do not accommodate a large-scale breeding program unless used to verify the results of *in situ* growth and yield tests (Hurd et al., 1972). However, Figure 7 and the information below illustrate the close relationship between root characteristics and field drought screening. Thus field screening by visual scoring would appear to be an indirect means of screening for root system development.

As drought progresses, absorption lags behind water loss during periods of peak evaporative demand. Adaptive mechanisms of the shoot, which help plants maintain a favorable water balance, include stomatal closure, a well-developed cuticle, and leaf rolling to impede water loss.

Stomatal closure has been investigated as a tool for determining the drought resistance of rices. Two reports (IRRI, 1973, 1975a), which

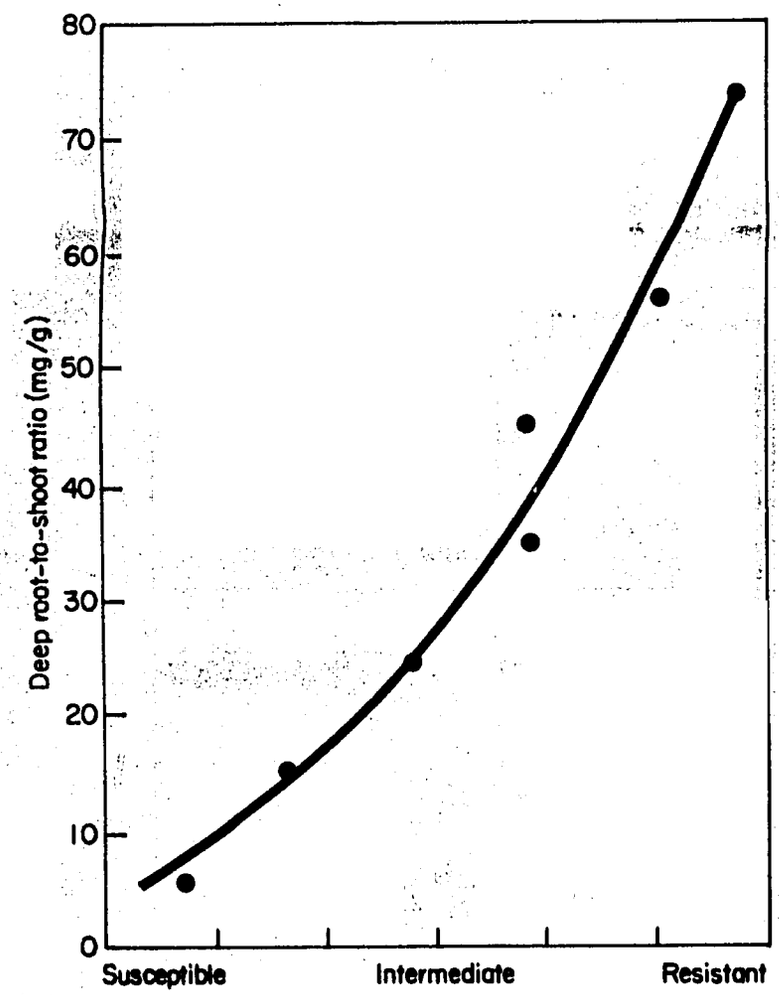
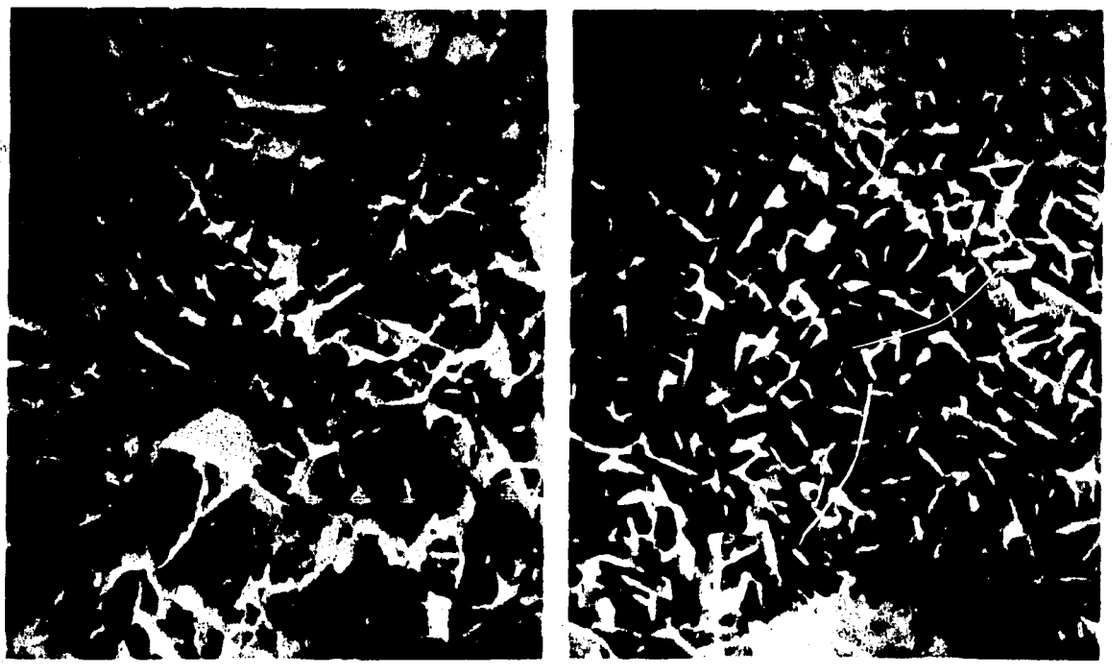


Fig. 7. Ratio of deep root-to-shoot of root below 30 cm/g shoot of rices is closely associated with the weighted average of upland field drought resistance scores (IRRI, 1976a).

compared rices from upland and lowland origins, generally found a higher stomatal resistance in upland than in lowland cultivars when both were subjected to moisture stress by either soil drying or addition of polyethylene glycol to plants grown in a nutrient solution.

Evaluation of stomatal behavior as an indicator of drought stress or as a tool for screening for drought resistance is problematic. The dynamics of stomatal resistance and the variability in the environmental factors that contribute to drought (Table 1) make the development of meaningful and repeatable screening procedures difficult. Stomatal resistance appears remote as a general selection criterion for drought resistance in rice.

High cuticular resistance is often mentioned as an attribute of drought-resistant species. Yoshida and de los Reyes (1976) compared the cuticular resistance of sorghum, corn, and several rice cultivars from different origins. They reported cuticular resistance values of 116 and 112 s/cm for sorghum and corn, respectively, and from 68 to 30 s/cm for the rice cultivars. These authors pointed out that several upland rices showed relatively high cuticular resistance values. It was subsequently found that the epicuticular wax deposition varied between rice cultivars with differing cuticular resistance values (Fig. 8).



63-83 x 13000 IR20 x 13000

Fig. 8. Scanning electron micrographs of the leaf surfaces of two rice varieties selected under varying hydrological conditions. 63-83, West African upland variety; and IR20, Philippine hybrid irrigated lowland variety. r_c is the cuticular resistance (s/cm). (Micrographs courtesy of Rothamsted Experiment Station, England). (O'Toole and Cruz, unpublished).

Quantifying of epicuticular wax by gravimetric methods has proven impractical in rice, whose wax contents are quite small. Ebercon et al. (1977) developed a colorimetric test to quantify wax removed by dipping sorghum leaves in chloroform. O'Toole, Cruz, and Seiber (unpublished) used gas-liquid chromatography to quantify the surface wax of rice obtained by dipping rice leaves in chloroform.

Leaf rolling, perhaps the most universally obvious symptom of drought, has been identified as a trait for resistance and, alternately, for susceptibility (Chang et al., 1972, 1974; Loresto et al., 1976). It indicates that turgor or pressure potential has decreased and the plant no longer completely avoids internal water stress.

The parallel trends of leaf rolling and leaf-water potential illustrated in Figure 9 suggest that leaf rolling is a good indicator of leaf-water potential. The association is generally true, but, it should be noted that across diverse cultivars it may not always be accurate.

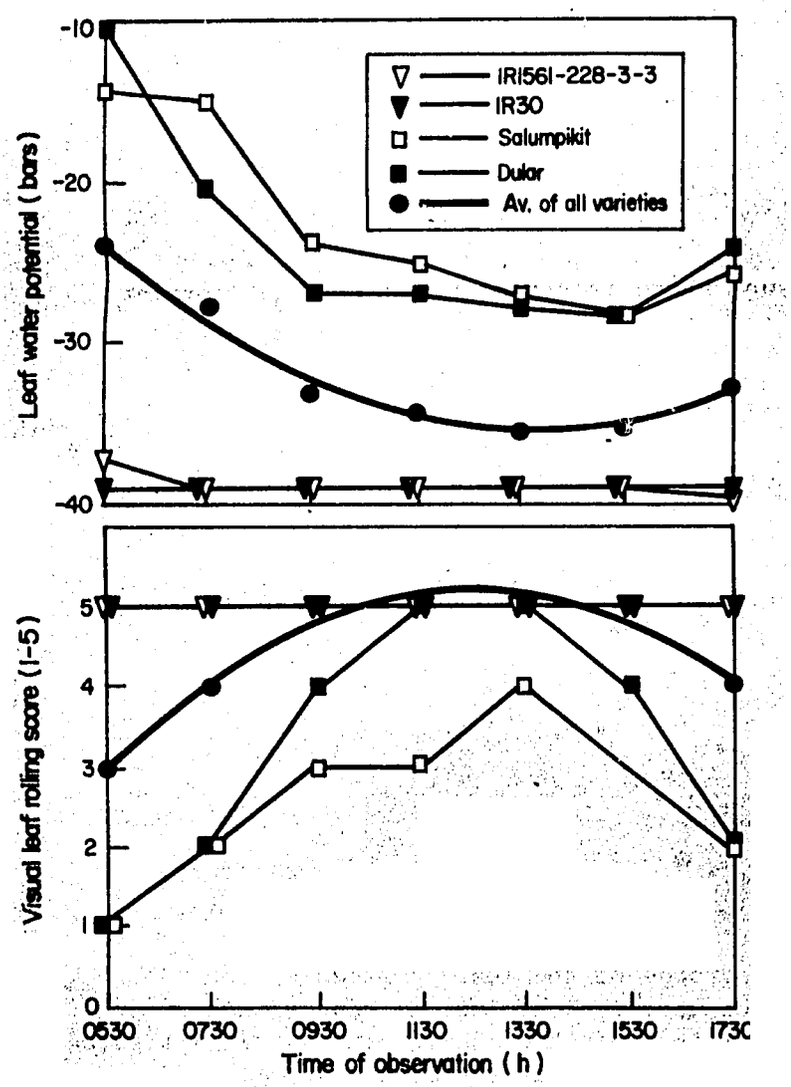


Fig. 9. Daily trends of leaf water potential a[illegible]ng taken from 16 cultivars during dry-season upland field drought screening at IRRI, 1976 (O'Toole and Moya, unpublished).

Figure 9 illustrates that cultivars differ in this characteristic. Dular and Salumpikit maintained higher leaf-water potentials throughout the day than the lowland hybrid cultivars IR 30 and IR 1561-228-3-3, and exhibited rolling and unrolling while the others did not.

Broad statements about the significance of leaf rolling alone are meaningless. We do not mean to imply, however, that this character is too complex to be used. On the contrary, its diurnal expression has been successfully used to identify plants capable of rehydrating overnight and thus indirectly allowing selection for root development (Chang et al., 1974; Loresto et al., 1976).

Recent efforts to provide a physiological basis for interpreting mass field screening carried out at IRRI during the dry season have emphasized the net effect of the various avoidance mechanisms as a substantial component of plant attributes being selected.

When the leaf-water potential of 16 cultivars was plotted against the visual score received at various times of day, it was evident that selection was for maintenance of leaf-water potential in this type of evaluation (Fig. 10). Since leaf-water potential rises to its highest level at dawn, it is at this time they show the greatest separation of varieties and reflect varietal differences in capability to rehydrate over the dark period (Fig. 9, 10). Thus the leaf-water potential at dawn may be a good indicator of a variety's root system development. Visual scoring also reflects this difference. In Figure 10, the slope relating maintenance of leaf-water potential to visual score is steepest early in the morning, and becomes flatter as leaves begin to roll and change to a duller color toward midday. These results have been instrumental in establishing the screening procedure of IRRI's drought screening greenhouse (IRRI, 1975a, 1976a).

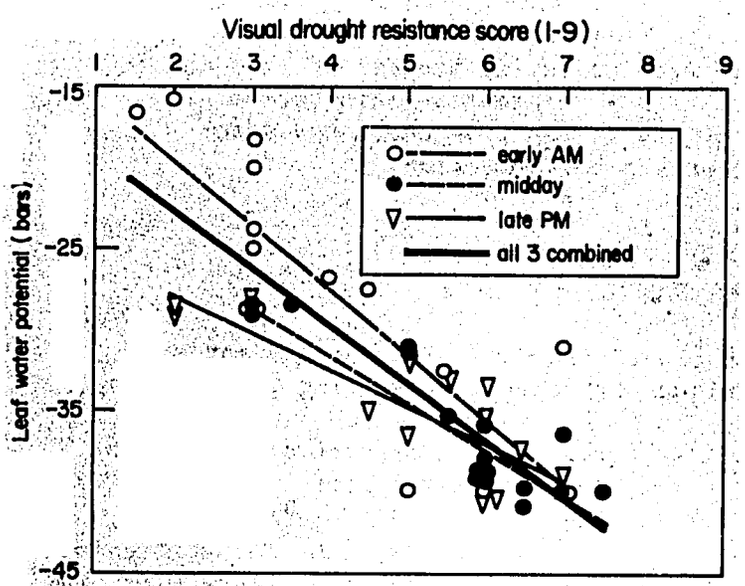


Fig. 10. Relationship between leaf-water potential and visual drought resistance score (1 = good, 9 = poor) for 16 rice cultivars during the dry season upland field drought screening at IRRI, 1976 (IRRI, 1977).

Tolerance mechanisms

In discussing plant tolerance for internal stress, authors too often use only examples of long-term or severe stress, probably because species or varietal differences become discernible only when extreme levels are reached.

Simple efforts to compare rice cultivars for drought tolerance began by exposing them to severe soil moisture stress with *Mimosa pudica* L. as a biological indicator of soil moisture deficits (IRRI, 1971; Chang et al., 1972). Later, more sophisticated methods were employed to subject rices to controlled levels of soil moisture tension. These techniques were also used to evaluate varietal response to soil moisture deficits at various growth stages (IRRI, 1973, 1974, 1975a). In 1974 (IRRI, 1975a), a seedling survival test (adapted from Wright, 1964) was implemented in the IRRI's phytotron where atmospheric moisture can also be controlled.

All the IRRI tests established that repeatable and significant variation in the capability of rice cultivars to survive severe soil and atmospheric moisture stress exist in the rice germ plasm (Table 2). In realistic terms the slow adaptation or hardening associated with tolerance tests or measures, possibly begins long before the severe conditions allow us to visualize the results. It is in the less-severe stages of plant stress when tolerance, or the precursory events of traditional tolerance demonstrated by severe stress, may be most beneficial. Currently, we lack the means of detecting germ plasm more tolerant of realistic levels of internal water stress.

Several tests reported in the literature as indicative of drought tolerance level have been evaluated at IRRI as possible selection tools: proline accumulation (IRRI, 1974, 1975a, 1976a), heat tolerance (IRRI, 1973); and seedling development in solutions with decreased osmotic potential (IRRI, 1975a). These tests have not as yet been adopted as screening tools in breeding for drought tolerance in rice primarily because of lack of knowledge about how the test results are related to yield-determining physiological processes, and about the levels of a *challenge* water deficit (degree and duration) desirable for selection.

SELECTION AND BREEDING FOR DROUGHT RESISTANCE

Little research has been directed toward breeding rice for drought resistance *per se* or to the techniques of selecting breeding populations for drought-resistant genotypes. A possible reason is the impracticability of separating drought resistance from agronomic performance or yielding ability. Recent reviews by Hurd (1971, 1976) on a range of cereals; by Bingham (1973) on wheat; by Ono (1971), Rao et al. (1971), Asana (1975), and Chang et al. (1975) on upland rice indicate the problems in approaching the subject. Future activities in breeding for drought resistance will largely depend on concurrent progress in physiological, ecological, and genetical researches.

The approaches used at IRRI and elsewhere illustrate the situation in rice.

Table 2. Summary of field scores on drought resistance of 9,720 varieties and lines, 1973-1976 dry season, IRRI, Plant Breeding Department.

Variety	Entries tested (No.)	Varieties (%) at vegetative stage with a score of									Entries tested (No.)	Varieties (%) at reproductive stage[1/] with a score of								
		1	2	3	4	5	6	7	8	9		1	2	3	4	5	6	7	8	9
Traditional upland varieties	2,326	0.1	1.9	13.7	28.2	44.0	10.0	1.2	0.9	-	528	0.2	-	4.9	4.4	10.8	7.6	39.0	3.4	29.7
African *sativa* varieties	471	-	0.2	6.8	34.8	32.5	20.8	3.2	1.5	0.2	303	0.2	-	4.6	0.9	6.3	4.6	31.6	2.0	51.1
Upland breeding lines of IRRI	1,432	-	0.1	2.2	18.0	46.3	27.8	5.1	0.5	-	639	-	-	0.6	-	2.5	0.6	42.1	3.3	50.9
Lowland breeding lines of IRRI	2,025	-	-	0.3	6.0	35.4	41.9	13.4	2.7	0.4	1,300	-	-	0.1	0.1	1.6	1.6	37.0	4.7	54.9
Upland breeding lines from other countries	312	-	0.6	-	4.8	34.0	42.0	13.5	3.2	1.9	94	-	-	2.1	-	1.1	-	45.7	9.6	41.5
Traditional rainfed-lowland varieties	326	0.6	14.4	8.0	22.1	24.2	27.3	3.4	-	-	326	-	0.3	0.6	0.3	3.4	-	21.8	4.6	69.0
Floating varieties	105	-	-	3.8	23.8	53.3	18.1	0.9	-	-	36	-	-	-	2.8	5.6	11.1	47.2	8.3	25.0
100-day varieties	969	0.1	21.1	9.9	20.9	28.6	16.7	1.8	0.6	0.2	969	0.6	1.6	6.8	3.0	9.7	6.3	25.6	11.8	34.6
ARC varieties (India)	361	-	11.4	13.6	28.2	24.6	19.4	2.8	-	-	361	-	0.2	2.4	1.7	8.9	4.7	19.7	1.7	60.7
Balu varieties of Indonesia	318	-	1.9	7.9	16.7	41.2	31.5	0.9	-	-	211	-	-	1.4	0.5	4.7	1.9	16.1	1.9	73.5
Salt-resistant varieties	127	-	-	3.9	32.3	46.5	17.3	-	-	-	127	-	-	-	-	-	1.6	33.8	11.8	52.8
Cold-tolerant varieties	151	-	-	-	29.8	68.9	1.3	-	-	-	151	-	-	-	-	4.6	0.7	7.3	7.9	79.5
O. glaberrima varieties	797	0.6	33.2	7.9	9.2	29.7	17.0	2.1	0.1	-	350	-	-	34.6	13.1	8.0	4.3	15.4	-	24.6
Total	9,720										5,395									

1/ Data on reproductive stage from 1976 dry season only.

Identifying promising germ plasm

Genetic diversity forms the foundation of all breeding programs. At IRRI the breeding program is greatly aided by availability to the breeders and problem area scientists of the genetic resources of more than 45,000 accessions of *O. sativa*. Moreover, thousands of breeding lines possessing high levels of disease and insect resistance are being developed in national breeding programs designed mainly for irrigated rice. African rices (*O. glaberrima*) and wild taxa further add to the rich gene pools.

Through a mass-screening technique developed at IRRI in 1973, more than 7,000 rice accessions and numerous breeding lines have been efficiently scored on the basis of their field reactions to drought at two growth stages (Chang et al., 1974; Loresto et al., 1976). An additional 2,000 accessions were scored for reaction to drought in field screening by IRRI agronomists.

Table 2 summarizes the drought ratings of nearly 10,000 rice accessions and breeding lines in tests during 1973-76. Varieties of *O. glaberrima*, mostly from Liberia, showed some of the highest levels of drought resistance at both the vegetative and reproductive stages. The traditional upland varieties of West Africa, South America, and Southeast Asia, and the *O. sativa* varieties collected from rainfed-lowland fields of West Africa also had high levels of drought resistance at both growth stages. The early maturing varieties frequently have high levels of drought resistance, mainly because of drought escape mechanisms. Resistance of the traditional rainfed lowland varieties of tropical Asia ranged widely from low to high. The floating or deep-water rices have intermediate field drought resistance. The resistance of semidwarf varieties varied from low to intermediate.

Among the lowland types, including the deep-water varieties, relatively few showed high drought resistance at the reproductive stage.

The relative rankings of the different variety-groups indicate their positive association with the frequency and severity of drought in the area from which the group was collected.

The ability of a rice strain to recover at the end of the water-deficit period has received as much attention as drought resistance at IRRI. The ability to recover was excellent in the rainfed-lowland *O. sativa* varieties from West Africa, in the *O. glaberrima* rices, and in the semidwarfs from lowland breeding nurseries. The traditional rainfed lowland varieties have quick to moderately quick recovery ability but the early-maturing lowland varieties and the traditional upland varieties have rather poor recovery ability.

The mass screening technique and the visual scoring scale for drought resistance are described by Chang et al. (1974), Loresto et al. (1976, and IRTP (1975). We found the drought resistance ratings obtained in dry-season tests at IRRI to be reproducible in yield trials planted in the wet season at other sites (when drought occurs) (IRRI, 1976, 1978) or in similar screening tests in other countries of Southeast Asia and West Africa.

Criteria in field testing and selection

During the dry season, we focus on the identification of drought-resistant and quick-recovering parents (varieties) and breeding lines. In the wet season, we do most of the progeny selection (plant or line) in early-generation populations and make an agronomic evaluation of fixed lines at two or more sites.

Selection in the upland rice breeding program is based on seedling vigor, moderate tillering ability, relatively high levels of drought resistance, moderate levels of drought-recovery ability, intermediate height (to improve nitrogen response and lodging resistance), resistance to blast and sheath blight, resistance to the major insects, a range of maturities to fit into different climatic zones, moderately long panicles having full exsertion, high panicle fertility and heavy grains, nonshattering habit, a stable base yield and the potential to respond to favorable nutrient-and-water regimes. We also pay attention to the consumers' preference for grain quality: intermediate (22-27%) amylose and low-to-intermediate gelatinization temperatures. When the rainfed testing sites exhibit adverse-soil factors, either because of native characteristics or those attributable to soil chemical changes due to drying (Table 1), we select for tolerance to the soil conditions as well.

In dry-season mass-screening experiments, we do visual drought resistance scoring and compare the test materials with a set of control varieties planted in the same block. Recovery is rated in a similar manner.

After thousands of entries had been scored for drought resistance, the early maturing (100 days or slightly longer) varieties were noted to be somewhat favored in the scoring process because of their escape mechanism. While we do not fully understand the physiological and histological mechanisms behind the springy process of leaf rolling and unrolling between 0700 to 1700 hours, we are certain that the selection pressure is indirectly for a deep-and-thick root system and the retention of turgor under stress. We also check the promising breeding lines to ensure that the deep-and-thick root system derived from outstanding upland varieties of the traditional type (Loresto and Chang, 1971; Chang et al., 1972) is being retained in the progenies. Moreover, the IRRI plant physiologist study the root-to-shoot ratios of different genotypes (IRRI, 1976a, 1977).

The delay in heading of the rice plant subjected to stress is a sensitive indication of its susceptibility to drought. We compare the upland planting with a concurrent planting in irrigated fields (mainly for seed increase) to estimate the delay in panicle initiation. We compare plant height in the same manner.

The percentage of grain-filling on the panicle and the 100-grain weight are also useful criteria in ascertaining reactions to drought that occurs during the reproductive phases.

Differences in grain yield often reflect inherent genotypic variation in yielding ability and are confounded by drought stresses and plant reaction to water deficit occurring at different growth stages when a wide spread

in maturity is involved. Therefore, we rely on the proportional reduction in yield within a genotype due to stress as an indicator of drought resistance or susceptibility.

By evaluating the agronomic performance of parents and breeding lines in the wet season at three sites -- which represent combinations of poor moisture retention and low fertility, intermediate moisture levels and fertility, and wet and fertile soil conditions -- we are able to assess the base yield and the potential yield of the test materials. We interpret our yield trials by graphically combining rainfall distribution, soil-moisture tension levels in relation to the onset of panicle initiation, date of harvest, and grain yield (IRRI, 1975a, 1976a).

Progress in breeding for drought resistance

Upland culture. Initially when single crosses were made between traditional upland varieties and semidwarf lowland varieties, we ran into great difficulty in recombining the drought resistance, plant stature, and panicle and grain characteristics of the upland type with the tillering capacity, recovery ability, and pest resistance of the semidwarfs. For instance, from the 111 F_2 populations planted in 1974 wet season, only 163 F_2 plants were selected (IRRI, 1974, 1975a). A genetic study using three marker genes later revealed that aberrant segregation occurred in six of the eight upland x semidwarf crosses whereas only one of three upland x upland crosses gave an atypical F_2 ratio (Hung and Chang, 1976). By using some of the panicle-fertile lines from the initial crosses instead of the upland parent in subsequent crosses, and by using three-way or double crosses, we overcame the difficulty in recombining the desired traits from two variety-groups.

Progeny testing indicates that drought-resistant progenies are obtainable only when one parent in the multiple-parent crosses is a drought-resistant variety (IRRI, 1976a). This finding confirms the heritable nature of drought resistance.

Tests made in 1976 show that marked progress has been attained in combining the drought resistance and yield stability of the traditional upland varieties with a higher tillering capacity, higher levels of insect resistance, and a yield potential approaching that of the semidwarfs under a range of environmental conditions (IRRI, 1976a, 1977). We must, however, evaluate the breadth of blast resistance over wide geographic areas, to incorporate additional resistances to sheath blight and to the whitebacked planthopper, and to assess farmers' acceptance of such a type intermediate between the traditional upland varieties and the high-yielding semidwarfs.

We have also repeatedly evaluated elite upland germ plasm from various sources. The varieties and lines developed in Brazil and Ivory Coast have high levels of drought resistance and blast resistance, but they lack such desirable agronomic characteristics as lodging resistance, attractive panicles and desirable plant height.

The breeding lines from the International Institute of Tropical Agriculture, Nigeria, generally lack drought resistance but have

excellent recovery ability. Some of the upland varieties of Japan have excellent drought resistance but are unadapted to the tropics in growth duration and pest resistance.

Rainfed-lowland culture. We began a systematic evaluation of diverse germ plasm during the 1976 wet season in rainfed-lowland fields where the soils are prepared wet (puddled) and the seedlings are transplanted. As the planting was hit by drought, plant manifestations such as leaf rolling and unrolling, reduction in tillering and plant height, death of lower leaves, delayed heading, panicle sterility, and incomplete panicle exsertion -- all found in upland tests -- were observed, although to a lesser degree. Many of the drought-resistant genotypes identified in upland screening were also drought resistant in the rainfed-lowland fields.

Fortunately, 1977 wet-season experiments in farmers' fields comparing irrigated, partly irrigated, and rainfed treatments encountered dry spells late in the crop season. All of the four early maturing varieties were able to escape the 4-to-5 week drought and suffered little yield loss in the rainfed treatment. The medium maturing varieties showed greater decreases in yield when no irrigation was provided. While two out of five late-maturing varieties produced almost practically zero yield, in the rainfed treatment three others gave fair yields (1.2 to 2.2 t/ha). These findings confirm the potential of varietal resistance and the importance of having drought resistance at the reproductive phase (IRRI, 1978).

Apparently, we have a long way to go before we can identify the appropriate parents for hybridization and develop mass-screening or quick-evaluation techniques. We also need more sites for rainfed-lowland testing to adequately sample the diverse soil-and-water regimes.

By channeling breeding materials from upland, fully irrigated, and rainfed lowland programs into one another, we believe that it will be feasible to develop a wide array of breeding lines that can fit into different edaphic and climatic niches. The IRRI breeding program draws its strength from the diversity of parent materials, the large number of crosses per year, the large size of F_2 popualtions, the interdisciplinary nature of the evaluation, the multisite testing with collaborating national centers, and the extensive exchange of breeding materials with country programs.

CONCLUSION

Drought is recognized and described as a complex problem affecting the yield of much of the world's rainfed rice. The emphasis on complexity serves to show that:

To be effective, any attempt to improve drought resistance of rice must be based on a thorough knowledge of and appreciation for the locational and temporal specificity that characterizes a particular drought condition.

The complexity of ecological conditions to which rice has been adapted, especially the breadth of hydrological conditions, indicates that great

variability of water-related adaptations exists within the germ plasm.

We hope that the latter point will encourage intensified research on the soil-plant-water relationships of the rice crop. Ultimately, the research effort will lead to more complete elucidation of the spectrum of adaptations and will enhance the techical development of selection methods.

Breeding for drought resistance in rice is a recent undertaking in tropical areas. The limited progress made to date is based on empirical testing and selection at experiment station sites. We can expect greater progress soon as intensified interdisciplinary research efforts increase the rice breeder's awareness of the physiological mechanisms available and place at his disposal effective criteria and techniques for selection.

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