Response of Sorghum and Pearl Millet to Drought Stress in Semi-Arid India

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Abstract

The wide range of environments in which sorghum and pearl millet are grown in semi-arid India can be grouped as variable, optimum (or near-optimum), and stored soil moisture types. Variations in specific plant responses such as phenology, leaf area development, root growth, and water-use efficiency under these three types of environments are discussed. Sorghum and millet are contrasted for their response to a variable moisture environment, and the response of sorghum grown under stored moisture during the postrainy season to terminal stress is described. Finally the role of timing, intensity, and duration of stress on grain yield is examined. Breeding and management strategies for obtaining consistently high grain yields should fully fake into account specific plant responses to the basic environment to which research is directed.

Résumé

Réaction à un stress hydrique du sorgho et du mil cultivés dans les zones semi-arides de l'Inde : Les milieux de culture du sorgho et du mil dans les zones semi-arides de l'Inde ont été classés en trois types : variable, optimal (ou relativement optimal), en conditions d'humidité résiduelle. Les variations des réactions spécifiques des plantes, notamment la phénologie, le développement de la surface foliaire, la croissance des racines et l'efficacité de la consommation d'eau dans ces trois types de milieu sont décrites. Le sorgho et le mil se distinguent par leurs réactions spécifiques à un milieu hydrique variable. On décrit aussi la réaction d'un sorgho à un stress hydrique à la fin du cycle, lorsque ce sorgho est cultivé après les pluies avec la réserve hydrique. L'effet de la date, de l'intensité et de la durée du stress hydrique sur le rendement en grain est évalué. Les stratégies de sélection et de gestion visant à obtenir des rendements en grain toujours supérieurs devraient prendre en compte les réactions spécifiques des cultures au milieu sous étude.

The variation in the duration and amount of rainfall in India, caused by the southwest monsoon, creates a broad range of rainfall environments across the semi-arid tropical (SAT) regions of the country (Kanitkar et al. 1968). When combined with soils of varying depth, texture, and slope, the result is an even broader range of moisture environments for farming. Grain sorghum and pearl millet fit primarily into the drier parts of this range, As soil moisture is the major determinant of crop production, their adaptation to moisture deficit conditions is important. The erratic rainfall during the monsoon makes it difficult to predict the timing and intensity of drought stress during this season. During the postrainy season (*rabi*), sorghum is grown on Vertisols with stored soil moisture, in which case the

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increasing level of drought stress, especially after flowering, is fairly predictable. Other differences between these two seasons are described by Sivakumar et al. (these Proceedings).

To understand plant responses to drought, one should fully study the temporal and locational specificity that characterizes a particular drought condition. In this paper we will first examine the three most characteristic moisture environments of SAT India; second, describe various crop responses such as development, growth, and water use, and grain yield under different patterns of drought; finally, discuss the implications of these responses in solving the problems posed by different types of drought.

Moisture Environments of SAT India

The basic types of moisture environments can be classified as variable, optimum or near-optimum, and stored soil moisture conditions (Quizenberry 1982). In each of these environments both the seasonal pattern and the amount of evapotranspiration (ET) depend upon the rainfall distribution, the potential ET during the season, and the soil characteristics. We will illustrate the differences in these three environments by discussing rainfall probability estimates (Virmani et al. 1982) and soil moisture budgets.

Rainfall Probability Analysis

We have chosen three locations for discussion: Jodhpur in Rajasthan state, and Nanded and Ahmednagar in Maharashtra state. Jodhpur has a short rainy season (11 weeks) with a monsoon rainfall of approximately 300 mm. The probability of receiving less than 20 mm of rainfall per week during the season is 50 to 70% (Fig. 1). Soils are primarily sandy, with low water-holding capacity. Thus, Jodhpur is a variable soil moisture environment, where drought during the season is frequent and unpredictable. Pearl millet is the main crop grown in this zone, with very few or no purchased inputs.

Nanded in eastern Maharashtra is in an assured

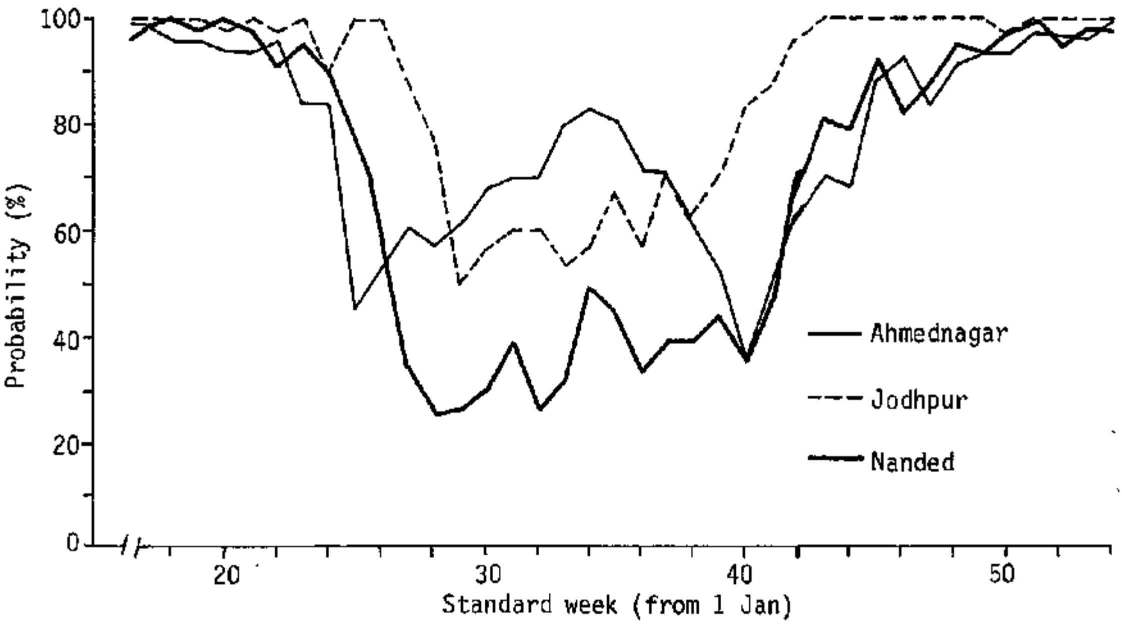

Figure 1. Probability of receiving <20 mm rainfall/week for three different moisture environments in India: Ahmednagar (19° 05'N, 74° 55'E), Jodhpur (26° 18'N, 73° 01'E), and Nanded (19° 08'N, 77° 20'E). The total rainfall, during the rainy season at these locations is 500, 300, and 810 mm, respectively; during the postrainy season, rainfall is less than 50 mm (adapted from Virmani et al. 1982).

rainfall zone with a longer rainy season (18 weeks) and a seasonal total of approximately 800 mm. The probability of receiving less than 20 mm of rainfall per week is much lower than that for Jodhpur (Fig. 1). Soils are deep Vertisols with high water-storage capacity; hence, sorghum is grown here in an optimum soil moisture environment. Towards the end of the season, rains are adequate to keep the profile sufficiently charged with water; hence an additional rabi crop can be grown on stored moisture.

Ahmednagar lies in the rain shadow of the Western Ghats mountain range, and, although the rainy season is of the same duration as in Nanded, the seasonal total is less than 500 mm. The probability of insufficient rainfall (<20 mm/week) during the rainy season is higher even than that at Jodhpur (Fig. 1). Both sorghum and millet are important in this district. Millet is grown on the shallow soils during the rainy season, and sorghum on the deep soils—similar to those at Nanded—with stored moisture during the postrainy season, following a rainy-season fallow or a short-duration pulse crop. The somewhat more reliable rains during the later part of the rainy season (Fig. 1) generally result in a fully charged soil profile at the beginning of the postrainy season and leave sufficient moisture for satisfactory crop establishment and growth, although drought may occur at the end of the season.

Soil Moisture Budgets

The partitioning of the seasonal total available moisture into its various end uses differs considerably in these three environments because of differences in rainfall, atmospheric demand, and soil characteristics. We have selected three sets of data on distribution and magnitude of various water-balance components—computed as described by Singh and Russell (1979) for three sorghum crops at Patancheru—to illustrate the differences between variable (Fig. 2a), optimum (2b), and stored soil moisture (2c) conditions.

Although there were small amounts of water available in the profiles at sowing in the medium-deep Alfisol (1977) and the deep Vertisol (1978), 80% or more of the total moisture available for the rainy-season crops came from rainfall received during the crop growth period. In the 1977 postrainy season, however, 72% of the seasonal moisture was stored in the soil at the time of sowing (Fig. 2).

Deep drainage (beyond the rooting zone) formed a significant portion (in both absolute and relative terms) of the water budget in both rainy seasons. In addition, during years of heavy storms, such as 1978, large amounts of water may be lost as surface runoff. Neither of these losses occurred during the postrainy season. Crop transpiration (T), in absolute terms was fairly similar in the three seasons (150, 200, and 130 mm for the rainy-season Alfisol and Vertisol and the postrainy-season crops, respectively). As a percentage of the total seasonal moisture, however, T varied from 19% to 66% over the three environments. Losses through soil evaporation (E) varied in direct proportion to the amount of seasonal rainfall received. Thus E during the postrainy season was minimum: only 15% of the total water budget and less than 25% of T (Fig. 2).

Finally, the moisture remaining in the profile at harvest varied from only 50 mm in the postrainy season (where the crop exhausts essentially all the available soil moisture in the root zone) to more than 200 mm in the high-rainfall Vertisol. In such Vertisols—in contrast to the Alfisol situation-extended and double-cropping possibilities are excellent.

Response of Sorghum and Millet to Drought

A precise study of plant responses during the rainy season is difficult, since the drought pattern varies widely across years. Hence, for the purpose of our study, we use the relatively rain-free summer (February-May) season to simulate various patterns of rainy-season stress. By withholding irrigations from the crop we are able to impose a stress of required intensity and duration at any time during its life cycle (Seetharama and Bidinger 1977). Due caution must be exercised; however, in extending these results to the rainy season; it has been necessary to confirm our results at specially selected, drought-prone sites during the normal rainy growing season. However, the response of sorghum grown during the postrainy season to terminal drought can be studied under natural conditions using a suitable irrigated control for comparison.

Crop Phenology

The effects of stress on the phenology of both sorghum and millet depend upon the severity of the

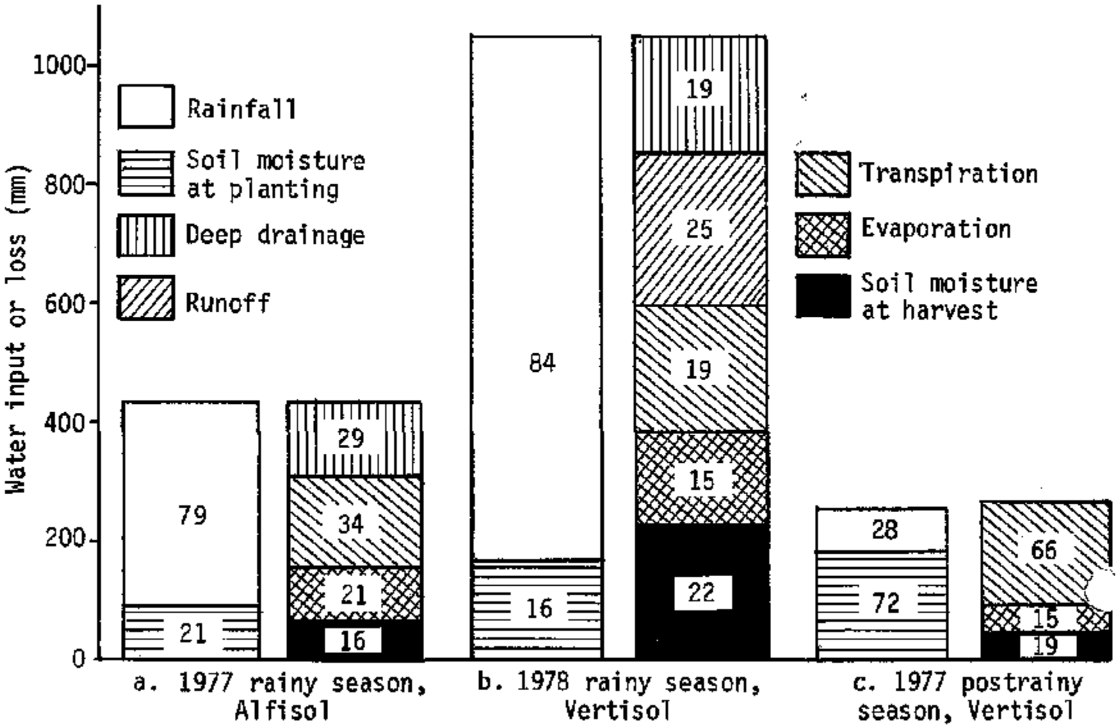

Figure 2. Seasonal water-balance components for Alfisols and Vertisols during the rainy and postrainy seasons at Patancheru, India. In each of the three sets (a-c), the left column represents the maximum quantity of water received during the season (stored moisture at planting + rainfall during the crop growth period); the right column, the various components of water loss through the system. The figures within each section of the column represent the quantity of water as percentage of the total input or loss from the system. Sorghum hybrids CSH-6 and CSH-8R were used during the rainy and postrainy seasons, respectively. Runoff was prevented during the 1977 rainy season by bunding. The maximum plant-available water-holding capacity of the Alfisol profile (127 cm deep) is 140 mm; that of the Vertisol (187 cm deep) is 240 mm.

stress itself (the degree and duration of plant water deficit) and on the stage of development of the crop at the time of stress. When the stress is not too severe, as often observed under near-optimum environments, the phenological responses are not apparent; effects are mainly on growth and yield. In the variable moisture environment, however, effects on phenology can be very evident, particularly when stress occurs before flowering. A comparison of the flowering patterns of two experimental hybrids of millet subjected to a period of severe stress between 20 and 45 days after sowing, illustrates this (Fig. 3). In the nonstressed conditions, mean flowering occurred at approximately 55 days for the earlier, high-tillering ICH-220 (Fig. 3c) and 60 days for the later, low-tillering ICH-162 (Fig. 3a), while the period of flowering was 20 to 30 days when both main shoot and tillers were considered. Under stress, the average flowering time was delayed by 10 to 15 days (occurring well after the termination of the stress), and the period of flowering was considerably extended. This was particularly obvious for ICH-220 (Fig. 3d), in which the tillers were delayed more than the main shoot.

Regular dissection of shoots during this experiment (Table 1) revealed that the delay in flowering in both main shoots and tillers in ICH-220 was due to a delay in development between floral initiation and flowering. In the late ICH-162, however, there was a delay in floral initiation in the tillers,'as well as

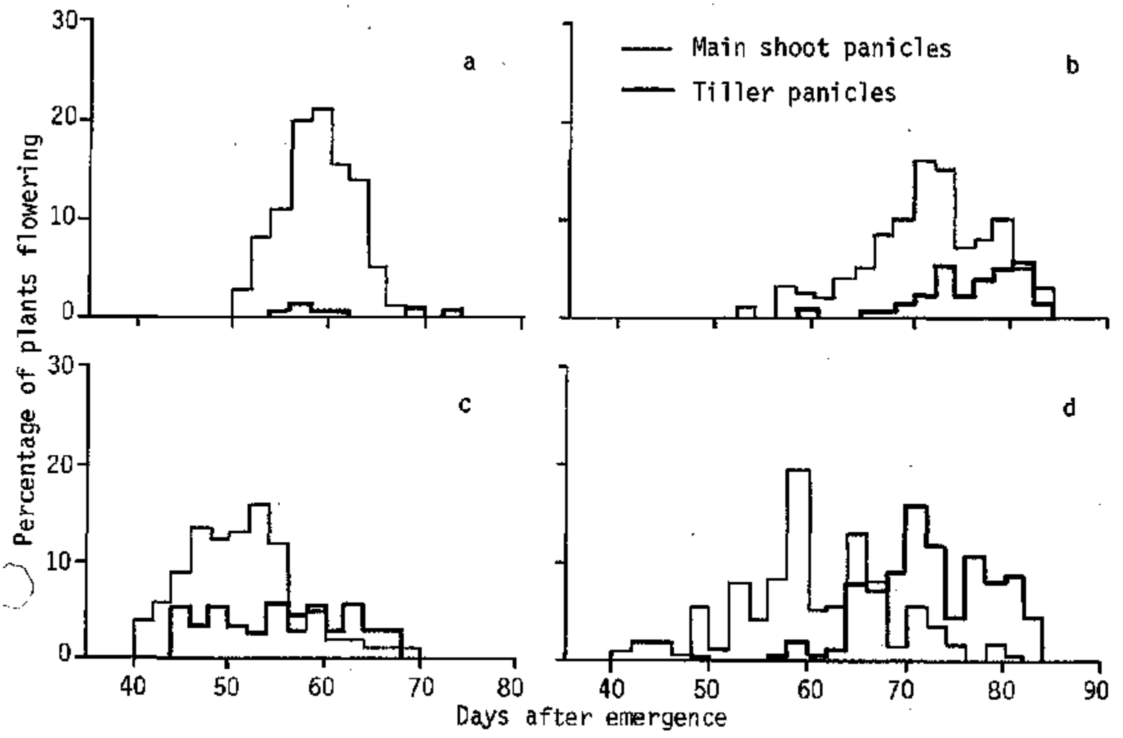

Figure 3. Frequency distributions of time of flowering of individual plants of pearl millet hybrids ICH-162 (a and b) and ICH-220 (c and d) in fully irrigated control (a and c) and stressed between20 and 45 days after emergence—treatments (b and d).

Table 1. Days from emergence to panicle initiation (PI) and flowering (F) for main shoot and individual tillers in two pearl millet hybrids under control and drought-stress conditions. (Irrigations were withheld between 20 and 45 days from emergence in stressed plots; Patancheru, summer 1982).

	Main shoot		First tiller		Second tiller		Third tiller		Fourth tiller	
Water treatment	PI	F	PI	F	PI	F	PI	F	PI	F
Hybrid ICH-220										
Control	18	49	26	54	27	54	28	51	32	63
Stress	18	58	25	69	26	71	28	78	28	72
Hybrid ICH-162										
Control	25	58	36	58	38	NF[1]	40	NF	41	NF
Stress	28	70	53	76	55	74	56	NF	57	NF

Source: V. Mahalakshmi and F.R. Bidinger. ICRISAT, unpublished data.

1. NF = Did not flower during the season.

a delay in subsequent development. Thus the responses are related to timing of the process affected: changes occurring before 30 to 35 days were not affected, whereas those occurring after this time were. Apparently the stress became severe enough at that point to affect panicle development.

The response of sorghum to a gradient of stress during the postrainy season was studied using a line source (Hanks et al. 1976) (Fig. 4). The mild

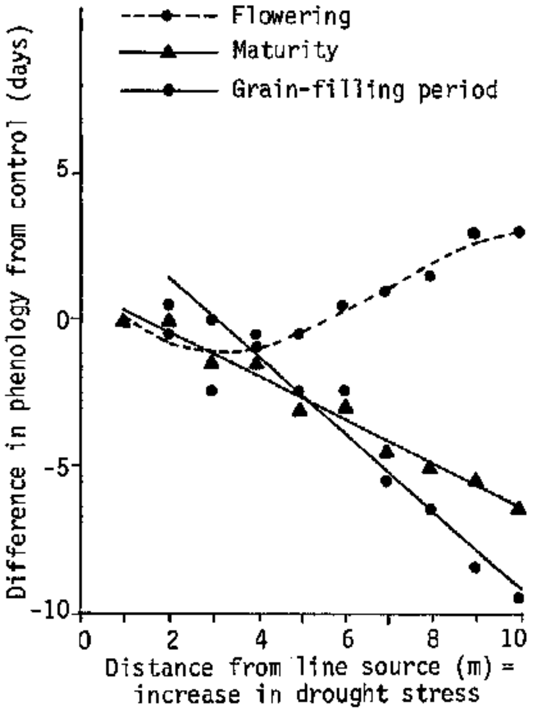

Figure 4. Effects of progressive drought stress on phenology of sorghum (cv CSH-8R). Data are from a line-source experiment; moisture gradient treatment started at 30 days from sowing and was repeated at 10-day intervals until maturity. In the plot nearest to the line source the water applied exceeded 80% of cumulative class A pan evaporation, values for the preceding 10-day period; flowering occurred at 73 days and maturity at 105 days. Regression equations: flowering $y = 75.30 - 1.63x + 0.20x^2 - 0.006x^3$ (r=0.99*); maturity: $Y = 1.44 - 0.50x$ (r=0.99***); grain-filling period; $Y = 4.83 - 0.89x$ (r=0.95***). 1980/81 postrainy season; ICRISAT, Patancheru, India.**

stress (very near to line source) during this cool season tended to accelerate flowering by a few days (probably due to increase in the temperature of the meristem). Further along the gradient, however, flowering was progressively delayed as the stress intensity increased. In some instances of severe stress, this kind of delay could extend for almost the whole period of stress (Seetharama and Bidinger 1977). Physiological maturity is invariably hastened with increasing intensity of stress, thus curtailing the length of the grain-filling period (and also the grain yield).

Crop Growth under Variable Moisture Environments

The basic difference in growth habit between sorghum and millet is expected to influence the response of each to fluctuating soil moisture. We compared their growth responses under adequately irrigated and stressed conditions (irrigations withheld between 14 and 60 days after sowing) during summer (Fig. 5). Millet maintains its superiority both in leaf area and dry-matter increase, and in net assimilation rate (NAR) early in the season, even under drought (Fig. 5a). It also recovers faster than sorghum (compare the dry matter or NAR increase after release; Fig. 5a and 5c, respectively) by rapid regrowth of the tillers However, sorghum still has higher dry matter at harvest because of its longer duration of growth, which is extended considerably more under stress than in millet (not shown in figure).

Leaf area of millet declines after the onset of stress; sorghum leaf development can remain "dormant" during the same period and resume later after the release of stress, even at the time when the leaf area in the regularly irrigated sorghum starts declining rapidly (Fig. 5b). Thus millet, with its shorter developmental phases, rapid regrowth, and greater plasticity conferred by asynchronous tillering (especially under stress), can make better use of short periods of water availability during short growing seasons in SAT India. The data in Table 2 illustrate the compensation for the reduction in grain yield of main shoot by increase in the yield of tillers (especially those developed after the release of stress; Table 1), In this experiment, the delay in tiller development has actually increased the grain yield significantly in' the high-tillering hybrid ICH-220 ($P<0.05$), in which the contribution of tiller panicles to the total yield under stress exceeded that of main-shoot panicles. In the low-tillering ICH-162, the contribution of tillers increased threefold under stress. However, when there is an opportunity for an extended season facilitated by late, more assured rains, sorghum is more productive than millet, as it can withstand longer periods of drought during the earlier phases of development, and still recover to produce higher grain and fodder yields.

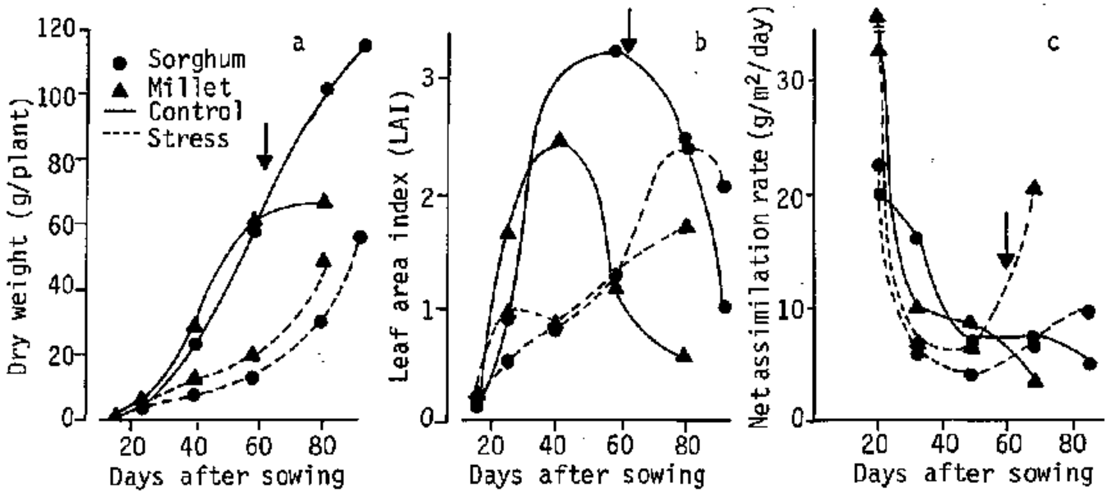

Figure 5. Dry-matter accumulation (a), leaf area changes (b), and net assimilation rate (c) of sorghum (CSH-6) and millet (ICH-425) under well-irrigated (control) and drought-stressed treat-ents during summer. Stress was initiated 14days from sowing. Downward arrows indicate the time of release of stress by irrigation (1983 summer season; ICRISAT, Patancheru, India).

Table 2. Grain yield and percentage contribution of main shoot (panicle) and tillers to total grain yield in pearl millet hybrids under drought-stress conditions. (Irrigations were withheld between 20 and 45 days from emergence in stressed plots; Patancheru, summer 1982).

			Percentage contribution of			
	Total grain yield (t/ha)		Main shoot		Tillers	
Hybrid	Control	Stress[1]	Control	Stress	Control.	Stress
ICH-220 (High-tillering)	2.6	3.0	68	44	32	56
ICH-162 (Low-tillering)	2.7	2.8	93	79	7	.21

Source: V. Mahalakshmi and F.R. Bidinger, ICRISAT, unpublished data.
1. Grain yields were not reduced by stress in either cultivar, as the growth duration was extended as shown in Table 1.

Sorghum Growth under Terminal Drought

The response of sorghum to stress—at the end of the season under receding soil moisture conditions on Vertisols during the postrainy season—was compared with that of an irrigated (unstressed control) crop (Fig. 6a). The relative transpiration rate (T/Eo; Fig. 6b) was about one-third of class A pan evaporation rate (Eo) at about 3 weeks after sowing. It reached the peak level of two-thirds of Eo at about 6 weeks, at which time the soil moisture also started declining rapidly, From then onwards the transpiration declined, unless the soil moisture was increased to high levels by irrigation. The seasonal transpirational water use was 160 mm for the dryland crop and 270 mm for the irrigated crop (which represented 95 and 90%, respectively, of the total water used in the season).

The dryland crop extracted a greater amount of the stored water from the profile (Fig. 6a) than the irrigated crop, since about one-third of its roots

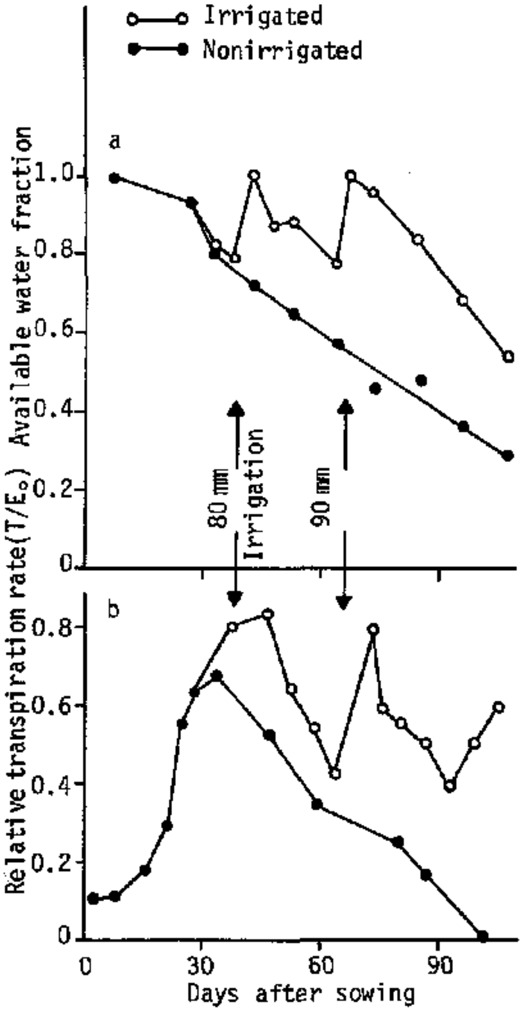

Figure 6. Seasonal changes in the (a) available water fraction in the 187 cm profile, and (b) transpiration/class A pan evaporation (T/Eo) ratios of sorghum under different moisture regimes on a Vertisol during the 1979/80 postrainy season at Patancheru. Transpiration was calculated by using the water-balance method of Singh and Russell (1979).

were in the soil layer 1 m below the surface (the irrigated crop had only one-sixth of its roots in this layer), although it had less dense roots in the profile as a whole at both stages of growth (Fig. 7). Thus "deep-rootedness" (Jordan and Monk 1980) is highly relevant under stored soil moisture conditions, especially in deep soils.

The dryland sorghum produced nearly the same grain yield as the irrigated crop because of greater use of stored moisture and better water-use efficiency (WUE, or ratio of yield ; water use).

Water-Use Efficiency

Under comparable management conditions the water-use efficiency (WUE) of millet can reach the level of sorghum, but generally millet WUE is lower (Table 3) (See also Kanemasu et al., these Proceedings). Both the grain yield and water use of millet are also lower than those of sorghum because of shorter crop duration. The WUE of sorghum grown on a deep Vertisol at Patancheru on stored moisture is higher than that of an irrigated crop (Table 4). Not only the genotype but also various management factors such as plant population, date of sowing, and application of fertilizers, mulches, and antitranspirants change WUE (see references in Tables 3 and 4).

Seasonal ET demands also influence WUE. For example, in both sorghum and millet the WUE is higher during the milder postrainy season than during summer. Under very severe drought conditions WUE can vary widely. We have plotted the WUE data of Lahiri (1980) and Mann and Lahiri (1979) against the reported seasonal rainfall for 4 years, two of which were very dry (Fig. 8). Under these conditions, WUE is clearly not a constant, and declines to very low values at rainfalls of less than 200 mm. No information was given on the seasonal distribution of rainfall in the papers cited above, but it is possible that evaporation was the major component of the ET if the rain in the dry years was received as very light showers. Thus ET under such conditions may not be a guide to potential production; the distribution of the rainfall may be the more critical factor, not only with respect to the time of the season at which the rain falls (as is commonly recognized) but also in the number and intensity of rainfall events, which may markedly affect the relative amounts of rainfall used for transpiration and other components of water balance.

Similarly the WUE of rabi sorghum was substantially higher at Patancheru on deep Vertisols than at Sholapur on shallower soils. While more than two-thirds of seasonal available water is used for transpiration at Patancheru (Fig. 2), only about one-third is used at Sholapur (Mane and Shingte 1982). At Patancheru WUE on Vertisols is lower than on Alfisols; under milder rabi conditions with reasonably assured moisture supply throughout the season,

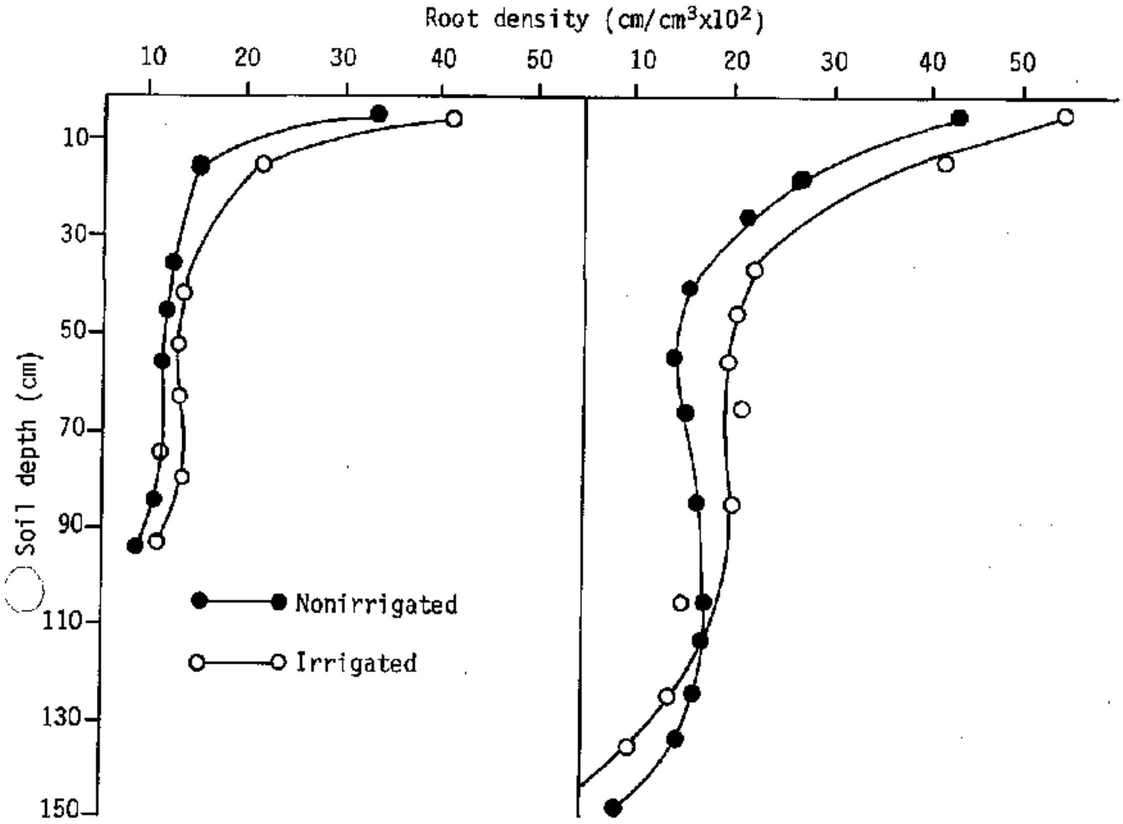

Figure 7. Effect of irrigation on root-density profiles of sorghum on a Vertisol at 57 (a) and 70 (b) days after sowing, 1979/80 postrainy season at Patancheru, India.

considerable yields and high WUE can be obtained with as little ET as 150 mm on the Alfisol (Table 4).

Effect of Stress on Grain Yields

Because periods of drought stress under variable environments, are unpredictable, generalizations on the effects of stress on grain yields are difficult, We have considered the effects during three basic stages of growth: seedling (between emergence and floral initiation), panicle development (between floral initiation, approximately 20 days after sowing, and flowering), and grain filling. The effect of stress on seed germination and crop establishment, especially in pearl millet grown in SAT India, is important, but the problem of seedling emergence will not be discussed here.

Stress during the seedling stage results primarily in poor crop establishment. Grain yields are reduced by such stress mainly through losses in plant stand. These losses may be general, or may occur in patches in the field; for example, in areas of shallow or light-textured soils. Stress occurring after crop establishment (but still within the seedling phase) generally has very little effect on grain yields either in millet (Lahiri and Kharbanda 1965; Lahiri and Kumar 1966) or in sorghum (Scientific Liaison Office 1974; Shipley and Regier 1970). This is particularly true for millet, where the nonsynchronous tillering habit provides plasticity in development during early stages (Rao et al, 1977).

Midseason stress has more severe effects on grain yield, and both the timing and the severity of such stresses are important. The effect of the time of termination of a period of midseason stress of 15 to 20 days duration on millet is illustrated in Figure 9. If the stress is terminated at or before flowering (of main shoot), the reductions in yield are small

Table 3. Seasonal evapotranspiration, biomass and grain yields, and water-use efficiency of pearl millet in semi-arid India.

Year/location	Seasonal evapotrans-piration (m)	Biomass (t/ha)	Grain yield (t/ha)	Water-use eficiency (t/ha per m) Biomass	grain	Soil type and treatment	Reference number
Rainy Season							
1968 Jodhpur	0.14[a]	1.17	0.02	8.4	0.2	Sandy loam: 20kg N/ha	1
1969 Jodhpur	0.07[a]	0.07	0.00	1.0	0.0	Sandy loam: 20kg N/ha	1
1970 Jodhpur	0.15[a]	5.56	1.85	37.1	12.3	Sandy loam: 20kg N/ha	1
1971 Jodhpur	0.18[a]	3.17	0.96	17.6	5.3	Sandy loam: 20kg N/ha	2
1974-77 Jodhpur	0.25		1.27		5.1	Sandy loam: mean of 60 and 120 kg N/ha	2
1977 Jodhpur	0.29	5.09[a]	1.74	17.6	6.0	Sandy loam: control crop	3
1973 Bawal	0.29	8.54	2.30	29.5	7.9	Sandy loam: control crop	4
1976 New Delhi	0.23	8.75		38.0		Sandy loam: mean of 4 cvs	5
1978 Patancheru	0.30	8.09	2.23	27.0	7.4	Medium-deep Alfisol	6
Mean	0.21	5.06	1.30	22.0	5.5		
Range	0.07-0.30	07-8.75	0.0-2.30	1.0-38.0	0.0-12.3		
Postrainy Season							
1977 Patancheru	0.16	5.99	1.86	37.4	11.6	Medium-deep Alfisol 60 mm rain + 3 irrigations	7
1977 Patancheru	0.10	3.13	1.10	31.3	11.0	As above except irrigations	7
Mean	0.13	4.56	1.48	34.4	11.3		
Summer Season							
1969-75 Rajendranagar	0.31 -0.42		2.14-3.53		6.9-8.4	Loamy sand: irrigated crop	8
Mean	0.37		2.84		7.7		

a. Calculated from data presented.

References

1. Lahiri (1980). 2. Krishnan et al. (1981). 3. Gupta (1980). 4. Vijay Kumar et al. (1977). 5. Misra and Nagarajarao (1981). 6. Reddy and Willey (1981). 7. ICRISAT (1978). 8. Reddy et al. (1980).

(< 20%), because this is a less sensitive stage of development, and tillers formed during the period of stress then complete development following the end of the stress. However, if the stress extends to the post-flowering period, yield reduction is more severe, as the opportunity to recover is gradually lost (Lahiri and Kumar 1966).

The effects of variation in severity of a midseason stress on millet is shown in Figure 9b (data from line-source experiment). Small deficits during this period have little effect on yield, and even severe deficits (essentially ho irrigation at all during the period) do not reduce yields more than 30%, again because of the recovery ability of the crop once the stress period is terminated. Stress during the grain-filling period, however, has far more drastic effects. Timing of such a stress is particularly important (Fig. 9a), yield being reduced as much as 70% if the stress period begins at or just before flowering. Similarly, the yield reduction due to varying levels of stress is linearly proportional to the severity of the stress during grain filling (Fig. 9b).

In rabi sorghum grown with stored moisture on Vertisols the degree of terminal stress would depend upon the amount of soil moisture available at flowering. About 17 kg of extra grain is harvested per hectare, for every additional 1 mm of water available during grain filling (Fig. 10).

Plant Responses to Drought: Research Imperatives

Two points applicable to all stress situations are:

Table 4. Seasonal evapotranspiration, biomass and grain yields, and water-use efficiency of sorghum in semi-arid India.

Year/location	Seasonal evapotrans-piration (m)	Biomass (t/ha)	Grain yield (t/ha)	Water-use eficiency (t/ha per m) Biomass	grain	Soil type and treatment	Reference number
Rainy Season							
1970 New Delhi	0.34		5.07		14.9	Sandy loam: cv Swarna	1
1977 New Delhi	0.32		4.38		13.7	Sandy loam: CSH-5 control crop	2
1978 New Delhi	0.30		3.32		11.1	Sandy loam: CSH-5 control crop	2
1978 Patancheru	0.43	9.83	4.47	22.9	10.4	Medium-deep Vertisol	3
1977 Patancheru	0.24	14.50	3.70	60.4	15.4	Deep Alfisol	4
1978 Patancheru	0.44	25.00	5.50	56.8	12.5	Vertisol, hydraulic lysimeter data	5
Mean	0.35	16.44	4.41	46.7	13,0		
Range	0.24-044	9.83-25.0	3.32-5.50	22.9-60.4	10.4-15.4		
Postrainy Season							
1970 Sholapur	0.14		0.69		4.9	90 cm black soil no rain during season: cold stress	6
1971 Sholapur	0.18		1.75		9.7	Rains during season 50 kg N/ha	6
1970 Sholapur	0.12	2.33	0.28	19.4	2.3	Medium-deep black soil control treatment	7
1973 Sholapur	0.19,	6.61	1.21	34.8	6.4	Medium-deep black soil control	7
1971 Sholapur	0.25	2.85[a]	0.69[a]	11.4	2.8	Medium-deep black soil control	7
1969-75 Rajendranagar	0.23		3.77		16.4	Sandy loam: irrigated	8
1977 Patancheru	0.21	5.10	2.43	24.3	11.6	Vertisol: stored moisture	9
1978 Patancheru	0.22	11.00	2.74	50.0	12.5	Vertisol: stored moisture	10
1977 Patancheru	0.32	9.30	5.99	29.1	18.7	Vertisol: irrigated	9
1978 Patancheru	0.41	14.50	3.13	35.4	7.6	Vertisol: irrigated	10
1978 Patancheru	0.25	11.66	5.43	46.6	21.7	Deep Alfisol: 6 irrigations	11
1978 Patancheru	0.15	7.09	2.71	47.3	18.1	Deep Alfisol: 4 irrigations	11
1978 Patancheru	0.48	22.50	8.55	46.9	17.8	Medium-deep Alfisols hydraulic lysimeter data: irrigated	5
1979 Patancheru	0.50	19.95	7.58	39.9	15.2	Medium-deep Alfisols hydraulic lysimeter data: irrigated	5
Mean	0.26	10.26	3.36	35.0	11.8		
Range	0.12-0.50	2.33-22.5	0.28-8.55	11.4-50.0	2.3-21.7		
Summer Season							
1969-75 Rajendranagar	0.34-0.50		2.76-4.53		8.10-9.10	Sandy loam: irrigated.	8
Mean	0.42		3.65		8.6		

i

a Calculated from data presented.

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I.Singh and Bains (1971). 2. Raghavulu and Singh (1982). 3.NatarajanandWilley (1980). 4. Singh and Russell (1979). 5.S.J. Reddy, ICRISAT, India; unpublished data. 6. Pharande et al. (1973). 7. Mane and Shingte (1982). 8. Reddy et al. (1980). 9. Sivakumar et al. (1979). 10. Sardar Singh, ICRISAT, India; unpublished data. 11. K.S. Gill, ICRISAT, India; unpublished data.

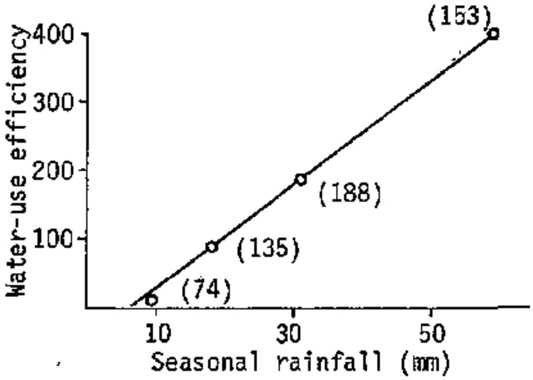

Figure 8. Calculated water-use efficiency (WUE; kg above-ground dry-matter at harvest/10 mm evapotranspiration per ha) in relation to total seasonal rainfall in pearl millet. Data are average of four to five cultivars per year, 1961-71. Figures in parentheses are the average reported seasonal water-use figures (in mm) for all genotypes for each year (adapted from Lahiri 1980).

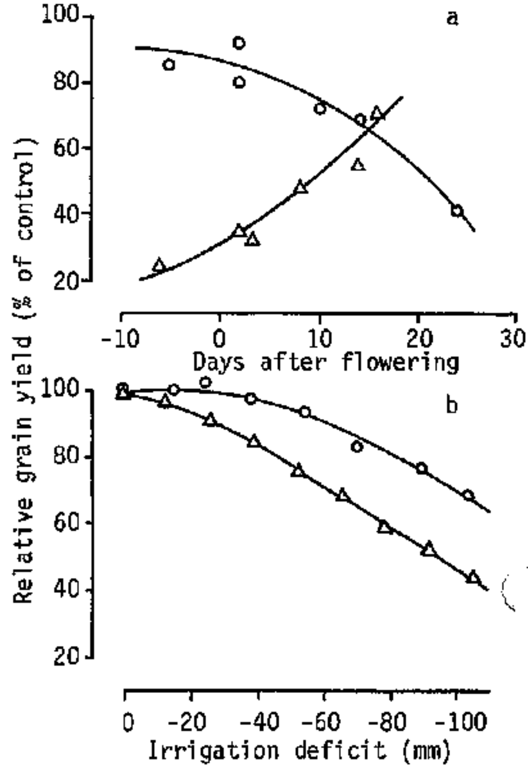

Figure 9a. Relationships between relative grain yield and the timing of stress (relative to time of flowering) in pearl millet on effect of time of termination of stress in relation to flowering, for a midseason stress of 15 to 30 days duration; △: effect of time of initiation, of terminal (end-of-season) stress in relation to time of flowering. (Data are averages of eight cultivars; 1978 and 1979 summer season experiments; F.R. Bidinger and G. Alagarswamy, ICRISAT, India, unpublished data.)

Figure 9b. Relative grain yield as a function of severity of stress (= irrigation deficit during stress period, in mm of water); o : for a 30-day midseason stress; rewatered at flowering; △: for a terminal stress begun at flowering. (Data are averages of 16 cultivars from the 1980 summer season; (V. Mahalakshmi and F.R. Bidinger, ICRISAT, India, unpublished data.)

(1) the duration of the variety must be matched to the expected period of available moisture and (2) the crop demand for water must be matched to the expected rate of soil water supply by adjusting plant population, fertility, or time of sowing. In peninsular India, replacing the traditional long-duration local cultivars of sorghum maturing after the cessation of rains with the early-maturing, high-yielding ones has been quite successful (Rao 1982), both in escaping possible terminal drought, and in allowing for flexibility in the time of sowing. Adjustment of farm practices to varying crop water demand is widely practiced by farmers in both sorghum- and millet-growing areas of India. Considerable research has also been done on management practices (Singh et al. 1980), although often the relationship of management and water availability or demand is not clearly spelled out.

Despite these generalities, the problems posed by drought are different in each of the three environments described earlier; consequently, varietal requirements and management practices for adaptation to these situations are also different. In an optimal environment, where high yields are possible with adequate management, the primary varietal requirement is high yield potential, to take full advantage of good moisture conditions (Quizenberry 1982). Smaller yield reductions under mild stress are strongly related to yield potential (Seetharama et al. 1982). Although the occasional short periods of drought at critical growth stages can reduce yield considerably, crop and soil man-

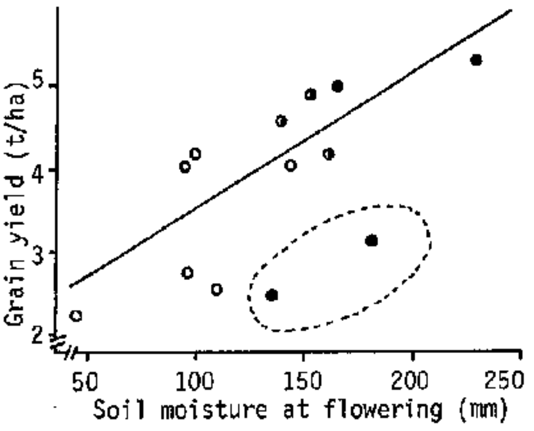

Figure 10. Relationships between total soil moisture at flowering during postrainy season in the upper 157 cm profile of a Vertisol and sorghum (cv CSH-8R) grain yield. o: nonirrigated; o, •: one and two supplementary irrigations before flowering, respectively. The two data points shown in the broken circle represent years in which response to irrigation was poor, due either to severe stalk rot or to very low nitrogen content in the profile; both are left out from the regression. Y = 1737-17x (kg/ga; r=0.81; data from Vertisol watersheds at Patancheru collected during the 1977-1982 postrainy seasons).**

agement techniques may be the best means of balancing yield and risk of drought in this environment.

In the variable moisture environment, drought can limit plant growth at any time during the season. Under such conditions crops must be able to take full advantage of periods of available moisture, to withstand periods of stress, and to resume growth rapidly when moisture is again available (Quizenberry 1982; Seetharama et al. 1983). Many of the developmental and growth characteristics and the higher heat resistance of millet (Sullivan et al. 1977) clearly provide adaptation to a variable moisture environment (Bidinger et al. 1982). Land and water management practices—especially to reduce runoff, and increase the moisture storage in the soil—are important. Intercropping sorghum and millets with a wide range of pulses (Singh et al. 1980) is a common practice in SAT India, which reduces the risk of crop failure in the system as a whole;

In the stored moisture environment the terminal stress is much more predictable; both breeding and cultural means can be effectively used to increase the amount of water available during grain filling by reducing the proportion of water used before flowering (Passioura 1976). Specific plant characteristics in the sorghum crop, such as deep roots, osmotic adjustment, and translocation of stem reserves to the grain (unpublished data; Sardar Singh et al., ICRISAT, India) improve performance under receding moisture conditions. Breeding strategy for sorghum for this season should be different from that for the rainy season (Seetharama et al. 1978).

Conclusions

Given the wide variability in drought stress due to variation in rainfall, soil water storage, and evaporative demand, plant responses to drought vary enormously. There is an urgent need to (1) classify the variation in crop environments in agronomically relevant terms and (2) quantify the usefulness of specific mechanisms of adaption to drought that are of practical value in each type of moisture environment. Finally, research and operational plans should be responsive to the needs of different moisture environments, as the relative importance of yield stability, risk minimization, and potential production will vary greatly among them.

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