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Integrating Genotype by Environment Interaction Analysis, Characterization of Drought Patterns, and Farmer Preferences to Identify Adaptive Plant Traits for Pearl Millet

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Abstract

The efficiency of crop improvement for variable stress environments can be enhanced if adaptive plant traits (morpho-physiological and developmental) can be identified. The desirability of a plant trait in an environment depends on the expected patterns of drought stress, the attitude of farmers towards risk, and on the specific requirements of the local farming system. The aim of this chapter is to identify plant traits for pearl millet that enhance adaptation to the harsh environments of Rajasthan (India), by combining analyses of drought patterns, genotype by environment (G×E) interactions, and farmers' preferences for plant traits. For environments covering the range of rainfall regimes in Rajasthan, we identified drought patterns by estimating plant-available soil water from long-term rainfall data. Environmental and genotypic causes of the G×E interactions were obtained from a multi-environment trial. Village studies provided information on farmers' responses to rainfall patterns and their preference for plant traits. A decline in rainfall in Rajasthan from east to west was associated with a shorter rainy season and increased, more unpredictable, occurrence of drought stress. The G×E interaction showed that phenology was an effective escape mechanism under terminal drought, but that developmental plasticity is required if the stress occurrence is unpredictable. Early flowering of pearl millet was of interest to many farmers across Rajasthan, but the preferred yield component ranged from a large panicle size in wet areas to high tillering (plasticity) in drier areas. This indicates the need for contrasting plant types across rainfall regimes. High tillering was said to improve the fodder value and to stabilize yield in dry seasons. This perception of risk avoidance in dry years was also evident in the practice of replacing pearl millet by a long-duration fodder legume and a short-duration dual-purpose legume for late plantings

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when drought is expected. Short-duration pearl millet varieties may provide farmers with more opportunities to adjust to the variability in the onset of the rains.

Introduction

Regions with large spatial and seasonal variability in the occurrence of abiotic stresses are often characterized by highly variable grain yields, large genotype by environment (G×E) interactions, and hence low selection efficiencies in plant breeding. Subsistence farmers in unfavourable environments are often interested in maximizing stability or risk avoidance, rather than maximizing average yield (Marshall, 1987). The optimum plant types for such environments will differ from those preferred under favourable conditions (van Oosterom and Ceccarelli, 1993). The development of a concept of an adaptive plant type is therefore a major challenge for a plant breeding program targeting variable stress environments (Richards, 1989).

Multi-environment trials that are conducted in stress environments can be used to identify major genotypic and environmental characteristics that determine the G×E interactions. For plant breeders, detailed analyses of such trials can give valuable information on the effects of plant types on yield (grain and fodder) and yield stability across environments. Conversely, an analysis of the trial environmental data can enhance our understanding of the major environmental constraints to yield and yield stability in a particular region. Multi-environment trials are generally conducted for only a few years, however, and are unlikely to sample the full range of seasonal variability for a certain location. This is especially so if the temporal variation is large, as is the case in many dry environments of the semi-arid tropics (Bidinger *et al.*, 1982; Sharma and Pareek, 1993). The effects of abiotic yield constraints vary considerably with the timing, severity, and frequency of their occurrence. An analysis of long-term meteorological data is in that case necessary to obtain reliable estimates of the probabilities of occurrence of certain stress patterns. It is essential that such an analysis takes into consideration the effects of these stress patterns on the crop (Lawn, 1988). Combining analyses of the frequency of occurrence of stress patterns with analyses of their effect on G×E interactions can test hypotheses on the adaptation of specific plant traits to defined stress environments.

The plant traits that are preferred by farmers are not only determined by the prevalent abiotic stress patterns, but also by requirements of the local farming systems and by the farmers' perception of risk and degree of risk aversion. Crop by-products other than grain, for example, are more valuable if livestock becomes more important in the farming system (Byerlee and Husain, 1993). Also, traits that cause uneven maturity (tillering) are more acceptable if farmers harvest by hand and not by machine (Lawn, 1988). But even within a farming system, farmers with different degrees of risk aversion may prefer contrasting plant types. In barley (*Hordeum vulgare* L.), different plant types are strongly associated with different yield responses across environments (van Oosterom *et al.*, 1993), which in turn affect the probability of a crop failure (Ceccarelli and Grando, 1991). To gain insight into the socioeconomic and biological reasons for farmers' preferences for plant traits, village-level studies of the local farming system are a necessity. Since many farm management decisions are based on knowledge of anticipated stress patterns, such village surveys complement analyses of stress patterns and of G×E interactions if plant types, adapted to the prevalent stress patterns and farming systems of a particular region, have to be identified.

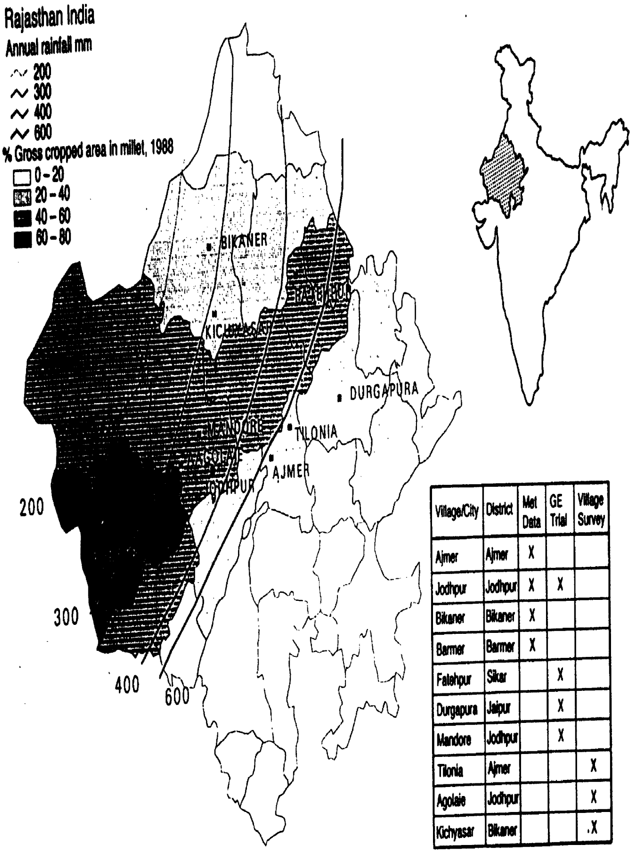
The aim of this chapter is to provide an example of the integration of an analysis of the G×E interaction for grain yield, a characterization of drought stress patterns, and village surveys on farmers' responses to rainfall patterns and their preference for plant traits, to identify plant traits of pearl millet (*Pennisetum glaucum* (L.) R.Br.) that enhance adaptation to the harsh environments in the Thar Desert of Rajasthan (northwest India). The preliminary results provide information on plant ideotypes which meet the expectations of farmers and match crop phenology with available soil water.

The farming environments of Rajasthan, India

The dry environments of Rajasthan are a good example of variable stress environments in the semi-arid tropics. Mean annual rainfall ranges from <300 mm in the west to >600 mm in the southeast (Fig. 20.1). However, annual fluctuations in rainfall are large and pearl millet grain yields of 50 kg ha^{-1} or less are not uncommon in western Rajasthan (Sharma and Pareek, 1993; Gupta *et al.*, 1994).

Pearl millet is the staple cereal in western and central Rajasthan and in parts in the west up to 80% of the gross cropped area is sown to pearl millet. It is usually sown in crop mixtures, but the range of feasible crops depends on the severity of rainfall constraints and on factors such as planting date and soil fertility conditions. Under the highest rainfall conditions, crops may include maize (*Zea mays* L.), post-rainy season crops (grown on stored soil moisture), chillies (*Capsicum annum* L.), and sorghum (*Sorghum bicolor* L.). With less rainfall, pearl millet, sesame (*Sesamum indicum* L.), and mungbean (*Vigna radiata* (L.) Wilczek) dominate. In the driest conditions moth-bean (*Vigna aconitifolia* (Jacq.) Marechal), guar (*Cyamopsis tetragonoloba* (L.) Taub), and pearl millet are grown. At all locations, normal crop mixtures include pearl millet, mungbean, sesame, mothbean, and guar, but mixtures in the western part typically have much more mothbean and less pearl millet and mungbean than those in central Rajasthan. In the west, where livestock (goats, sheep, and cattle) are an important part of the farming system, pearl millet and legume residues are valuable fodder sources.

Improved cultivars account for more than 50% of the area sown to pearl millet in India as a whole, but adoption has been limited at locations with lower and less reliable rainfall, such as western Rajasthan. Average yields of pearl millet in Rajasthan have not increased over the past decades (Jansen, 1988). On-station research results suggest that in the harsh environments of western Rajasthan, the released, high-yielding varieties have no yield advantage over the traditional landraces (Weltzien R. and Witcombe, 1989; Bidinger *et al.*, 1994). Increasing productivity through well-adapted, improved cultivars and management practices therefore remains a challenge in the Rajasthan environments.



Village/City	District	Met Data	GE Trial	Village Survey
Ajmer	Ajmer	X		
Jodhpur	Jodhpur	X	X	
Bikaner	Bikaner	X		
Barmer	Barmer	X		
Fatehpur	Sikar		X	
Durgapura	Jaipur		X	
Mandore	Jodhpur		X	
Tilonia	Ajmer			X
Agolaie	Jodhpur			X
Kichyasar	Bikaner			X

Fig. 20.1. Map of Rajasthan, giving the gross cropped area (%) in pearl millet per district, rainfall isohytes, and the location of the villages and cities used in the analyses.

Materials and Methods

Genotype by environment interaction for grain yield

Data on the G×E interaction for grain yield of pearl millet in Rajasthan were obtained from a multi-environment trial, comprising 14 genotypes (seven hybrids, seven varieties) grown across seven environments with different timing and intensity of drought stress (Table 20.1). These environments were a subset of a larger experiment (van Oosterom *et al.*, 1996). Because the hybrids tended to outyield the varieties, the analysis of grain yield across environments was restricted to the G×E interaction, using a principal component analysis (after removing the main effects from the data matrix) similar to the Additive Main effects and Multiplicative Interaction (AMMI) analysis (Gauch, 1988; Zobel *et al.*, 1988).

Characterization of drought patterns

For the characterization of drought patterns, we used long-term daily rainfall records for four locations spanning the range of annual rainfall levels within the major pearl millet-growing area of Rajasthan: Ajmer (26°27′ N, 74°37′ E, 87 years) in the wetter central part of the state, and Jodhpur (26°18′ N, 73°01′ E, 84 years), Bikaner (28°00′ N, 73°18′ E, 83 years) and Barmer (25° N, 71° E, 56 years) in the west. Mean seasonal rainfall (calculated from five days before to 80 days after the estimated sowing date) was 432 mm at Ajmer, 304 mm at Jodhpur, 229 mm at Bikaner, and 239 mm at Barmer.

Rainfall records were first used to estimate sowing dates and duration of the rainy season for each year at each location (310 combinations). Sowing was

Table 20.1. Grain yield, rainfall (for the season and until 40 days after emergence (DAE)), and the correlation between grain yield and date of flowering for 14 pearl millet genotypes, grown across seven environments in Rajasthan, India.

Environment	Grain yield (g m^{-2})	Rainfall (mm) Season	Rainfall (mm) Until 40 DAE	Correlation
No drought stress				
Durgapura 1988	324	458.7	271.2	+0.43
Post-flowering drought stress				
Fatehpur 1988	212	304.5	252.0	–0.84***
Mandore 1989	124	251.9	182.4	–0.35
Mandore 1988	91	139.1	134.7	–0.79***
Durgapura 1989	82	420.6	420.6	–0.05
Jodhpur 1988	63	194.7	165.3	–0.88***
Pre- and post-flowering drought stress				
Fatehpur 1989	47	110.2	75.0	+0.51+

+, ***: significant at $P<0.1$ and $P<0.001$ respectively.

assumed to be possible if at least 20 mm of rain fell within 3 days, in showers exceeding 5 mm. Under these circumstances, emergence is in general within 3 days. Only sowing dates from 1 June onward were considered because rainfall is too erratic and undependable before that date (Virmani *et al.*, 1982). The end of the rainy season was defined as the last day before the end of October receiving at least 5 mm of rain. In cases when this last shower was <10 mm, a second condition, the occurrence of another rainy day (at least 5 mm) within 2 weeks before the last rain, was added. This additional condition excluded isolated late rains of <10 mm. The duration of the rainy season was calculated as the difference between the sowing date and the date of the last significant rainfall.

Rainfall records were subsequently used to estimate crop-available soil water, using a simple soil water budget (Frère and Popov, 1979). In this budget, crop-available water is estimated from daily rainfall plus stored soil moisture, whereas the amount of water required for crop growth is estimated from potential evapotranspiration (PET), multiplied by a crop coefficient.

In addition to daily rainfall and sowing date, the budget requires the following input data:

1. *PET.* Daily data were obtained by interpolating monthly means for each site (Rao *et al.*, 1971). The mean value was assumed to occur at day 15 of each month. Although this fixed value of PET caused some error in the calculation of water availability, PET values are generally much more stable across years than is rainfall.
2. *Soil water holding capacity.* Soils in Rajasthan are very sandy (often >80% coarse and fine sand). The soil water holding capacity was set to 80 mm at Ajmer, 60 mm at Jodhpur, and 50 mm at Bikaner and Barmer. The lower values at the drier sites reflect the higher proportion of fine sand in western Rajasthan as compared to the central part of the state.
3. *Crop coefficient.* This is the crop evapotranspiration as a fraction of PET. Crop coefficients were adapted from those reported by Dancette (1983) for pearl millet of different duration in a Sudanian–Sahelian environment. They increased from 0.3 at emergence to 1.0 at flowering and then decreased to 0.6 at maturity. Two crop durations were assumed: 80 days (released varieties), and 65 days (very early modern hybrids). The difference in season length was assumed to be due to a more rapid growth early in the season of the short-duration material. No attempt was made to adjust the crop coefficient and crop duration in case of severe mid-season drought stress. The duration of the grain filling period was set to 25 days (Craufurd and Bidinger, 1988).

The balance between water supply and requirement was calculated for 5-day intervals, starting 5 days before the estimated sowing date. Since sowing is usually done directly after the first significant rainfall, the effect of stored soil water at sowing could be ignored. The output of the water budget was expressed as a crop water sufficiency index (WSI), defined as the percentage of estimated seasonal water requirement actually met by available soil moisture. At sowing, WSI is 100. This value remains 100, until the water requirements exceed the available water. The deficit, expressed as a percentage of the estimated seasonal requirement, is then subtracted from 100. If rainfall exceeds the soil water holding capacity, the excess is considered to be lost through run-off or deep percolation. Actual rainfall adjusted for these losses will be referred to as effective rainfall. Due to its simplicity, the water budget may not be as effective as the relative transpiration (ratio of actual transpiration to potential transpiration) in explaining grain yield differences (Muchow *et al.*, Chapter 18, this volume). None the less, WSI at maturity can be an effective predictor of possible grain yield in semiarid tropical environments where yields are mainly limited by drought: for pearl millet, an adjusted r^2 of 0.76 across 24 Indian environments has been found by van Oosterom *et al.* (1996).

A frequency distribution of the occurrence of certain types of drought stress at each site was obtained by classifying the 310 environments according to the presence of severe drought stress before or after flowering. The classification was based upon the seasonal pattern of WSI for an 80-day crop duration. Severe pre-flowering drought stress was supposed to occur if the cumulative WSI at 55 days after sowing was <80. Severe post-flowering drought stress was assumed if the change in WSI between 55 and 80 days after sowing was >20 units. Since *ca.* 60% of the seasonal water requirement occurs before flowering and 40% afterwards, a decrease of 20 units in the WSI indicates that about one-third of the water requirement before flowering and half the requirement after flowering was not met.

Village surveys

A study of farmers' preferences for different cultivar characteristics in pearl millet began in 1992 at locations in Ajmer, Jodhpur, and Bikaner districts of Rajasthan (Fig. 20.1). Farmers were exposed to a range of plant characters in new cultivars through on-farm farmer-managed trials in which they grew improved pearl millet cultivars alongside their own varieties. Participating farmers evaluated the experimental cultivars relative to their own varieties, and then described the traits of an ideal pearl millet cultivar for their farming situation. In addition, they discussed important production constraints in their farming systems, including crop management under different kinds of drought stresses. Details about the surveys have been given by Weltzien *et al.* (1996).

Results

Analysis of genotype by environment interaction for grain yield

The G×E analysis of multi-environment trials (Table 20.1) was used to explore the effects of plant type of grain yield under different drought stress patterns. The biplot for G×E interaction of grain yield (Fig. 20.2) showed that the genotypic component of the interaction was strongly associated with earliness, since early- and late-flowering genotypes had opposite interaction patterns. The first two interaction principal component axes, which explained >80% of the interaction for grain yield, were both associated with flowering date and accounted for 84.5% of the variance in mean days from emergence to flowering.

The effect of genotype earliness on grain yield differed with the kind of drought stress. Early-flowering genotypes had a positive yield interaction with the

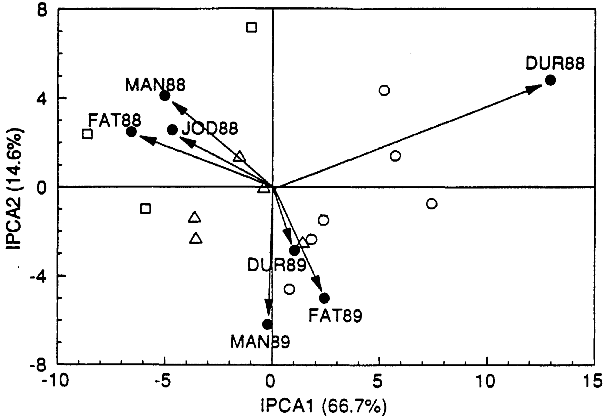


Fig. 20.2. Biplot of the AMMI model for 14 pearl millet genotypes, grown in seven environments in Rajasthan. Genotypes are grouped according to flowering into early (□), medium (△), and late (○). Environments are marked by '●'. For a list of environments see Table 20.1.

environments of Fatehpur, Jodhpur, and Mandore in 1988 (Fig. 20.2), because they escaped the end-of-season drought in these environments (Table 20.1). Their interaction was negative with Durgapura 1988 (Fig. 20.2) as there, escape did not play a role because drought stress was absent (Table 20.1). Early genotypes had a negative yield interaction with Fatehpur 1989, where intermittent drought occurred before the flowering of the early genotypes. Late genotypes escaped drought in this environment, because of a delay in flowering (data not shown). At Mandore and Durgapura in 1989, a relationship between flowering and grain yield was absent, notwithstanding the presence of post-flowering drought stress (Table 20.1). For Durgapura 1989, this was due to the absence of interaction *per se* (Fig. 20.2), whereas at Mandore 1989, interaction was not associated with average time of flowering. Early flowering was thus advantageous in case of post-flowering drought, whereas late genotypes performed better under intermittent drought stress.

The GxE interaction analysis indicates the potential importance of different developmental rates for different patterns of drought stress. Although the trials included only two seasons, Fig. 20.2 illustrates the importance of the genotype by year interaction, resulting from different stress patterns in the 2 years. The importance of different plant types for specific locations therefore depends on the frequencies of occurrence of different patterns of drought stresses in those locations. These frequencies can be estimated from long-term rainfall records.

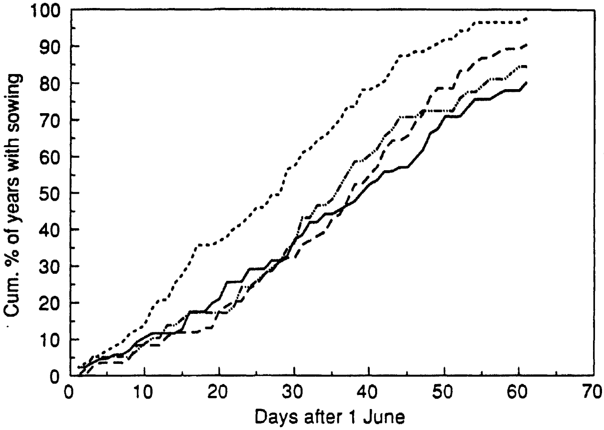


Fig. 20.3. Cumulative proportion of years when sowing had taken place on or before a certain date after 1 June for four locations in Rajasthan: Ajmer (......), Jodhpur (------), Bikaner (———), and Barmer (-·-·-·-).

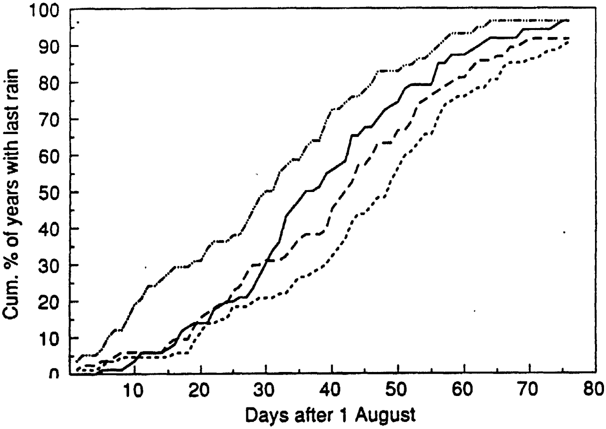


Fig. 20.4. Cumulative proportion of years when the last significant rainfall occurred on or before a certain date after 1 August for four locations in Rajasthan: Ajmer (......), Jodhpur (------), Bikaner (———), and Barmer (-·-·-·-).

Table 20.2. Farmers' estimates (n=30) of the onset of the monsoon during the period 1990–1992 in three districts in Rajasthan (1992 Village Surveys).

Year	Onset	Ajmer	Jodhpur	Bikaner
1990	Early	23%	0%	7%
	Normal	33%	100%	13%
	Late	43%	0%	80%
1991	Early	23%	0%	0%
	Normal	77%	100%	0%
	Late	0%	0%	100%
1992	Late	100%	100%	100%

Table 20.3. Probability that the rainy season will exceed 80 days for different sowing dates at four locations in Rajasthan. Probabilities are based on normal-distribution estimates of observed dates of last significant rainfall.

Sowing date	Ajmer	Jodhpur	Bikaner	Barmer
5 June	0.87	0.81	0.82	0.66
15 June	0.75	0.66	0.64	0.46
25 June	0.57	0.47	0.42	0.27
5 July	0.38	0.29	0.22	0.13
15 July	0.22	0.15	0.09	0.05
25 July	0.11	0.07	0.03	0.02
Median	0.50	0.25	0.16	0.12

Onset and duration of the rainy season

The length of the rainy season is determined by the timing of the arrival and withdrawal of the southwest monsoon. Normally, the monsoon arrives first in southeastern Rajasthan and withdraws from northwest to southeast at the end of the season. The median sowing date at Ajmer (central Rajasthan) based on long-term rainfall records, was 29 June, whereas it was *ca.* 9 days later at the drier locations in the west (Fig. 20.3). The last significant rainfall occurred on average earliest at the driest locations (Bikaner and Barmer) and latest at Ajmer (Fig. 20.4). The duration of the rainy season is thus in general longer in eastern Rajasthan.

Timing of the onset of the monsoon in Rajasthan is variable in both time and space (Fig. 20.3). The likelihood of a late onset of the rainy season was greatest in the driest locations. In Ajmer, an opportunity to sow before the end of July occurred in most years, but at the drier locations the probability of no such opportunity ranged from 10% at Jodhpur to 20% at Bikaner (Fig. 20.3). This variability in the onset of the monsoon was also evident from the perceptions of farmers. For the period 1990–1992, farmers in Bikaner felt that the monsoon had been late in all seasons, whereas in Jodhpur and Ajmer most farmers felt it had been late in only one of the seasons (Table 20.2).

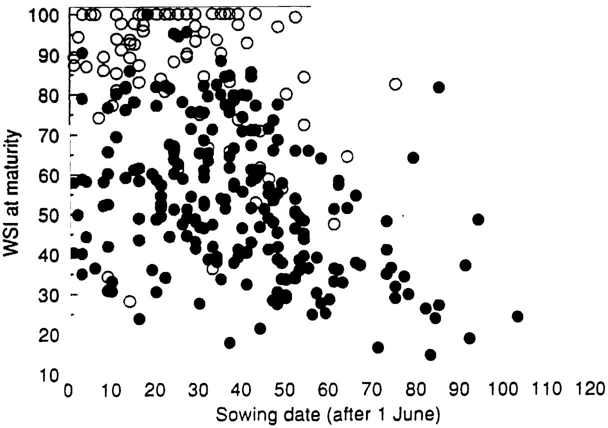


Fig. 20.5. Estimated water sufficiency index (WSI) at maturity, plotted against date of sowing for Ajmer (○) and the three dry locations Jodhpur, Bikaner, Barmer (●).

The timing of the end of the rainy season was independent of the sowing date ($P>0.43$ at each site). Therefore, once a crop has been sown, the expected duration of the rainy season depends entirely upon the distribution of the timing of the last rain. This occurrence was normally distributed at all locations. Thus, for any sowing date the probability that the duration of the rainy season exceeds a certain number of days can be estimated. The probability of a rainy season exceeding 80 days is >50% at Ajmer if sowing occurs in June, but declines rapidly with later sowing (Table 20.3). At Jodhpur and Bikaner, this probability falls below 50% once sowing is delayed until the last part of June, and at Barmer at even earlier sowing dates. Since such an early sowing is very unlikely in western Rajasthan, the improved varieties with *ca.* 80 days crop duration are very likely to experience drought stress during grain filling, especially if sowing is later than normal.

Late sowing had a strong negative effect on seasonal water availability (WSI) at the dry locations. The highest observed WSI at maturity at these locations in general declined linearly if sowing was delayed past early July (Fig. 20.5). This was almost entirely due to post-flowering drought stress. As a result, the date of sowing significantly affected the probability of a crop failure (WSI at maturity <30) at the dry locations. At Bikaner and Barmer, for example, the probability of WSI at maturity falling below 30 increased sharply if sowing was delayed until the middle of July. This was in contrast to the situation at Ajmer, where environments without serious drought stress (WSI at maturity >80) were common, even if sowing was done at the end of July (Fig. 20.5).

Effects of sowing date and crop duration on water availability patterns

Environments were grouped based on the expected occurrence of severe pre- and post-flowering drought stress (Table 20.4). At Ajmer, most years (72%) experienced no or only mild drought stress. At Bikaner and Barmer, by contrast, severe pre- and post-flowering drought stress prevailed in at least half of the years, whereas years with no or even mild drought stress were rare. At Jodhpur, the occurrence of drought was more variable and all types of drought stress occurred regularly. The χ^2 for the distribution of years among the four groups of stress patterns was non-significant ($P>0.30$) at all locations, indicating no association between drought occurrence before and after flowering. The differences between locations in the frequency of occurrence of the major drought patterns (occurrence in >10 years) were associated with differences in sowing dates: the average dates of sowing for years with the same pattern of drought stress were relatively similar across locations where >10 years of data were available (Table 20.5).

The effect of sowing date on the seasonal pattern of water availability was studied in more detail by comparing cumulative effective rainfall of years with early (1–10 June), intermediate (21–30 June) or late (16–25 July) sowing for each location. If sowing occurred in early June, the first month of the growing season tended to be dry (Fig. 20.6). After this dry start, the cumulative effective rainfall increased sharply, as the rains not only met the crop requirements, but also filled the soil

Table 20.4. Distribution of years over four classes of occurrence of severe drought stress at four locations in Rajasthan. Values in parentheses give frequencies (%).

	Severe drought stress class			
Pre-flowering	No	Yes	No	Yes
Post-flowering	No	No	Yes	Yes
Ajmer	63 (72)	3 (3)	19 (22)	2 (2)
Jodhpur	26 (31)	8 (10)	33 (39)	17 (20)
Bikaner	6 (7)	13 (16)	13 (16)	51 (61)
Barmer	5 (9)	7 (13)	16 (29)	28 (50)

Table 20.5. Mean sowing dates (expressed as days from 1 June) for four classes of severe drought stress, at four locations in Rajasthan. Bold values are means of at least 10 years (see Table 20.4). Means in a row followed by a different letter are significantly different ($P<0.05$).

	Severe drought stress			
Pre-flowering	No	Yes	No	Yes
Post-flowering	No	No	Yes	Yes
Ajmer	**24.2a**	42.7bc	**38.6c**	11.5ab
Jodhpur	**28.7a**	26.6a	**40.9b**	**56.5c**
Bikaner	37.3ab	**24.6a**	**37.0b**	**44.8b**
Barmer	15.2a	20.6a	**36.9b**	**45.8b**

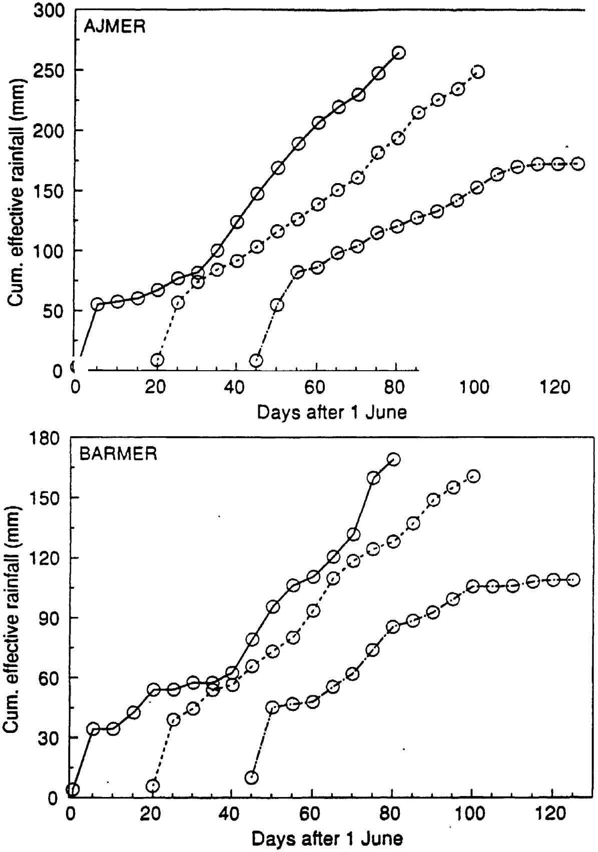


Fig. 20.6. Estimated cumulative effective rainfall for an 80-day growing season at (a) Ajmer and (b) Barmer for three classes of sowing dates: 1–10 June (——), 21–30 June (------), and 16–25 July (·······).

profile. A crop that was sown in late July generally received adequate rainfall early in the season, but limited rainfall during grain filling. Years where severe drought occurred after flowering indeed had on average a significantly later sowing date than those with less or no drought stress during grain filling (Table 20.5). Sowing in late June gave on average the best match between phenology and rainfall pattern (Fig.

Table 20.6. Mean water sufficiency index at maturity for crops maturing in 65 or 80 days, at four locations in Rajasthan for three different classes of sowing date.

		Site			
Sowing	Duration (days)	Ajmer	Jodhpur	Bikaner	Barmer
Early	65	71.1	55.2	38.1	37.6
1–10 June	80	85.0***	66.1*	42.3	49.9*
Medium	65	91.8	65.5	53.4	51.0
21–30 June	80	90.3	68.5	55.9	57.0*
Late	65	86.8	62.1	43.1	49.6
16–25 July	80	74.8*	53.8**	41.6	40.2*

*, **, ***: Means significantly different at $P<0.05$, $P<0.01$, and $P<0.001$ respectively, according to a *t*-test for paired observations.

20.6), resulting at all four locations in the highest average WSI at maturity, for both normal and short duration crops (Table 20.6).

A crossover type of interaction between crop duration and sowing date was observed for WSI at maturity (Table 20.6). Normal-duration varieties were particularly vulnerable to terminal drought stress following late sowing, whereas short-duration varieties were adversely affected by mid-season drought when sown early. Using paired (by year) observations, normal-duration crops (80 days) had at three sites a significantly higher WSI at maturity at three locations if sowing was in early June, but a significantly lower WSI following sowing in mid-July (Table 20.6). The difference in general was non-significant if the crop was sown by the end of June.

Farmers' response to the onset of the monsoon

The differences between locations in the duration of the rainy season and the probability of stress occurrence may affect the way that farmers respond to the timing of the onset of the monsoon. Farmers expect a higher rainfall season with an early onset of the rains, and a lower rainfall season if rains start late. This is supported by the rainfall analyses (Figs 20.5 and 20.6). Therefore, many farmers adapt their crop mixtures in response to the timing of the first significant rains. While most farmers in the drier locations do not vary their normal cropping mix if they are able to sow early, some farmers in Bikaner said they would increase the proportion of pearl millet and sesame (Table 20.7), two crops which respond better to increased rain than mothbean and guar. For similar reasons, Ajmer farmers switch to maize, sometimes chillies, and/or sow a post-rainy season crop (rabi crop) if they can sow it early (Table 20.7).

When rains are late, all surveyed farmers in the west, and about half in the east, change their cropping patterns. In the west, the probability of an adequate season length (Table 20.3) and water availability (Fig. 20.5) becomes so low with late sowing, that sowing pearl millet is hardly worthwhile. Under such circumstances,

Table 20.7. Percentage of farmers that increases the proportion of a certain crop in the crop mixture as a response to early or late onset of the monsoon at three locations in Rajasthan. Values in parentheses give the number of farmers surveyed. (Data are from the 1992 village survey.)

	Ajmer (30)		Jodhpur (30)		Bikaner (30)	
	Early	Late	Early	Late	Early	Late
% farmers changing crops	54	57	0	100	30	100
Maize	43	0	0	0	0	0
Rabi crop	30	0	0	0	0	0
Chilli	10	0	0	0	0	0
Pearl millet	0	50	0	0	27	0
Sorghum	0	50	0	0	0	0
Sesame	0	7	0	3	10	3
Mungbean	0	27	0	33	0	13
Mothbean	0	3	0	73	0	97
Guar	0	0	0	97	0	87

farmers in Jodhpur and Bikaner replace pearl millet by mothbean (a short-duration, dual-purpose grain legume), guar (a long-duration fodder legume) or mungbean (a medium-duration, dual-purpose grain legume) (Table 20.7). At Ajmer, the prospects for a pearl millet crop are good, even if sown late (Fig. 20.5). Farmers plant pearl millet and sorghum under such conditions (Table 20.7), to ensure production of, at a minimum, some fodder.

Farmers frequently cannot sow all their fields after the first rain, as the top soil dries out rapidly due to its sandy nature. In addition, fields often have to be re-sown because of poor plant establishment. Farmers also often change their cropping patterns if they have not been able to sow a field until after the second or third rain or if they have to re-sow. Most surveyed farmers in Ajmer and Jodhpur had not re-sown any pearl millet fields in the previous three seasons, but in Bikaner all farmers had re-sown at least once. The re-sown fields were treated like late-sown fields with less pearl millet and more mothbean and guar in the crop mixtures.

The practice of changing the cropping pattern in response to the occurrence of the first rain is widespread, especially in western Rajasthan. This practice is motivated by considerations of stress escape and risk avoidance.

Farmers' preferences for different plant traits

Discussions with farmers about preferred traits of a 'perfect' pearl millet variety were used to assess the importance of different plant traits to farmers in three locations. The characteristics mentioned by farmers were grouped into three categories (Table 20.8): (i) estimates of productivity (grain and fodder yield); (ii) productivity components (panicle size, grain size, tillering); (iii) adaptation (earliness, water needs). Individual farmers mentioned additional traits, but only in limited numbers.

Grain yield and yield components (panicle size, grain size, tillering) were

Table 20.8. Percentage of farmers using a characteristic to describe an ideal pearl millet variety or compare an improved pearl millet cultivar with their own cultivar (1992 and 1994 village surveys).

	Ajmer	Jodhpur	Bikaner
Cultivar character	1992 survey	Avg 1992/94 surveys	Avg 1992/94 surveys
No. of farmers surveyed	22	32	34
Estimates of productivity			
High grain yield	32	59	61
High fodder yield	23	28	39
Productivity components			
Large panicle size	77	75	43
Large grain size	45	38	26
High tillering	27	69	68
Adaptation			
Earliness	55	50	58
Low water needs	0	9	39

important at all locations, but farmers' emphasis on traits to attain these high yields gradually shifted if rainfall at their location became more erratic. In Ajmer, farmers focused on large panicles and large grains to increase yield. In Jodhpur they wanted large panicles for grain yield and high tillering for fodder. In Bikaner, farmers focused on tillering to achieve both high grain and fodder yields. They also expect high tillering to stabilize grain and fodder yields in dry seasons. Farmers in Bikaner put a low priority on large grain size, possibly because of quality concerns, as they preferred the quality of their own smaller-grain varieties. Fodder yield was given higher priority in the west than in the east, due to the importance of pearl millet stalks as animal feed.

Stress escape was the main determinant of the G×E interaction and a major reason for farmers to change crops in response to the timing of the first rain (sowing date). The importance of earliness was expressed by about 50% of the farmers at all three locations, not only for drought escape but also for earlier food availability. Although earliness can play an important role in escape of end-of-season drought, earliness *per se* is not enough for many farmers. Low water requirements were noted as a characteristic of a perfect variety by almost 40% of the farmers in the driest location, but never mentioned explicitly in Ajmer. Drought escape is thus an important aspect of farmers' varietal preferences, both explicitly and implicitly, but the plant type by which farmers ensure this depends on both the rainfall pattern and the farming system.

Discussion

The pearl millet plant types that are preferred by farmers in Rajasthan were related to the prevalent patterns of drought stress that occurred at the various locations.

Drought patterns affected trait preference directly through farmers' considerations of environmental adaptation, and indirectly through the socioeconomic requirements of the local farming system. At all locations, trait preferences were guided by drought escape and risk avoidance.

Phenology

Earliness is a useful adaptive mechanism in situations of terminal drought. This was evident in the results of the G×E interaction analysis of the multi-environment trial (Table 20.1) and in the finding that short-duration varieties have an advantage if sowing occurs in July (Table 20.6). Earliness was desired by many farmers across Rajasthan and in fact is a feature of the local landraces from Jodhpur and Bikaner districts. These flower in general earlier than the standard released cultivars, and maintain a rather stable flowering time across a range of stress environments (E. Weltzien R., personal communication).

Although landraces flowered early on average, the range in flowering dates within groups of landraces from western Rajasthan was *ca.* 2 weeks (E. Weltzien R., unpublished data). This genetic variability may provide population buffering to stabilize performance in environments with variable stress occurrence (Ceccarelli *et al.*, 1992). Since these landraces are the result of a long process of farmers' selection in these dry environments, the range in flowering dates suggests that it may be difficult to identify one single optimum phenology for a certain location. Sowing a mixture of varieties might then be a good strategy to enhance the prospects of escape. This is a common practice in Namibia, where farmers are willing to sow 'longer season' landraces if early rains occur, combined with a later sowing of short-duration varieties (D.D. Rohrbach, Bulawayo, personal communication). In Rajasthan, the partial resowing of fields in case of poor establishment has a similar effect on enhancing drought escape. Earliness is thus an important plant trait in Rajasthan, but not sufficient to escape stress in variable stress environments.

Developmental plasticity

Developmental plasticity has been recommended for environments where unpredictable intermittent stress occurs (Ludlow and Muchow, 1990). The need for plasticity in Rajasthan was obvious in our study by the large contribution of phenology to the G×E interaction for grain yield (Fig. 20.2, Table 20.1). No single phenology can always escape stress if the timing of stress occurrence is variable. Apart from sowing cultivar mixtures, plasticity in determinate crops can best be achieved through non-synchronous tillering. This increases the range in flowering and ensures better crop recovery after intermittent drought stress is relieved (Mahalakshmi and Bidinger, 1986). Non-synchronous tillering and ability to recover are features of the landraces from western Rajasthan.

The occurrence of drought was relatively predictable at Ajmer: the probability of severe post-flowering drought was four times higher than that of pre-flowering drought (Table 20.4). This predictability of drought occurrence was consistent with the farmers' particular concept of the ideal pearl millet variety. Farmers in Ajmer put most emphasis on a large panicle size, and consequently reduced tillering (Table 20.8), suggesting that developmental plasticity was not the major concern to them. In Bikaner, by contrast, the timing of drought occurrence was more variable, as both intermittent and terminal drought stress were common (Table 20.4). High tillering was by far the most important plant trait, because farmers felt that it would stabilize both grain and fodder yields in case of drought. Tillering may have a grain yield penalty in favourable years, but the chances of a favourable season are so slim at Bikaner (Table 20.4), that this yield penalty has little practical consequences. Farmers therefore prefer minimizing the risk of a crop failure over maximizing yield in an occasional favourable season. At Jodhpur, the intermediate location in terms of stress patterns, farmers' preferences for plant traits were a combination of those of Ajmer and Bikaner, as they were interested in both large panicles and high tillering. These traits are hard to combine in one variety, and further surveys should inquire if farmers could achieve this through planting mixtures of varieties. Considering the highly variable stress patterns at Jodhpur, with all types of drought stress likely to occur, such a mixture might be a safe strategy to ensure some yield in poor seasons and exploit high yields in more favourable seasons. The differences between locations in farmers' perceptions of the yield structure of an ideal variety thus reflect the intensity and predictability of stress occurrence.

The preference for tillering in Western Rajasthan was also associated with the socioeconomic needs of the local farming system. Tillers improve the feed quality of the stover, particularly when the stover is not chopped before feeding. Tillering does cause an uneven maturity, but in the farming systems of Rajasthan, where re-sowing of parts of a field is a common practice, this is accepted.

Farmers' response to the onset of the monsoon

Farmers in Rajasthan make many of their management decisions in an environment of high uncertainty. Knowledge of the probability of occurrence of certain stress patterns as the season unfolds enables them to adjust their decisions to these probabilities, a practice known as response farming (Stewart, 1988). The duration of the rainy season in Rajasthan is related to the occurrence of the first rain, and hence the probability of drought stress. Similar results were reported for the major pearl millet growing areas of western Africa (Sivakumar, 1988). Therefore, farmers use this occurrence of the first rain (sowing date) as an important signal to adjust the crop or variety mixtures they sow to the anticipated rainfall. In Ajmer, half of the survey farmers increased the proportion of pearl millet in their mixture if sowing is late (Table 20.7), to assure themselves of at least fodder yield in case of a late drought. Shorter duration cultivars might provide these farmers with a means of growing more pearl millet in late seasons and increase the likelihood of grain yield. In western Rajasthan, the practice of increasing the proportion of guar *and* mothbean in late-sown crops emphasizes the farmers' preference for risk avoidance. Guar, a long-duration and drought tolerant fodder crop will ensure at least some fodder yield, whereas mothbean, a short-duration dual-purpose crop, may provide some grain yield through drought escape in addition to some fodder. The fact that nearly all farmers increase the proportion of both crops corroborates the results of the water budget analysis (Fig. 20.5), which showed that water availability is so low if sowing is delayed beyond the end of July in the western locations (Fig. 20.5), that sowing pearl millet is hardly worthwhile. Availability of short-duration pearl millet might be useful to complement longer-duration pearl millet and could provide the farmers with an additional means of adjusting to the variability in the onset of rains and to the need to resow fields lost to early-season drought stress.

Contrasting plant types are required for the different rainfall zones of Rajasthan. The variability in stress occurrence needs a breeding strategy based on populations. Impact requires the availability of appropriate genotypes and regular access of farmers to multiple genotypes. The ICRISAT–ICAR (Indian Council of Agricultural Research) collaborative pearl millet breeding program for Rajasthan is targeting the development of such distinct varieties and populations for the individual zones of Rajasthan. Future work should explore with farmers the potential roles of varieties of different maturity for specific situations like late sowing or poor soils and explore the constraints to and oppor-tunities for introducing and maintaining multiple genotypes locally.

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