GENOTYPE x ENVIRONMENT INTE:RACTIO:NS AND STABILITY OF GRAIN YIELD AND SOME OTHER C:HARACT:ERS IN PEARL MILLET [*Pennisetum americanum* (L.) Leekel

by

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INTRODUCTION

Genotype x environment interaction is of major importance in developing improved genotypes in plant breeding. The existence of large genotype x environment interaction poses a major problem of relating phenotype performance to genetiç performance. It makes difficult the selection of superior genotypes and inhibits progress from selection. Therefore, it is important to understand the nature of genotype x environment interaction to make testing and selection of genotypes more efficient.

The relative performance of genotypes often varies from one environment to another, i.e., there exists genotype x environment interaction. Testing on a large scale covering a wide range of environmental conditions is needed to identify genotypes that interact less with the environments or possess greatest stability.

This study was conducted to evaluate the stability and adaptation of millet hybrids across environments in Nebraska and Kansas. The specific objectives of this study were as follows:

- to determine the nature of genotype x environment interaction for grain yield, days to 50% bloom, plant height, 100-seed weight, and seeds/m^2;

- to determine the stability of the hybrids for the different traits and identify the adapted hybrids.

LITERATURE REVIEW

It is commonly observed that the relative performance of different genotypes varies in different environments, that is, there exists genotype x environment interaction. The presence of genotype x environment interaction contributes to the unreliability of crop yield over a wide range of environments. It is in general agreement among plant breeders that interaction between genotype and environment has an important influence on the breeding for better genotypes. The occurrence of large genotype x environment interaction makes the selection of superior genotypes difficult and inhibits progress from selection. It prevents the full understanding of genetic control of variability. Methods such as stratification of environments have been proposed to reduce the magnitude of genotype x environment interaction, but this was of little help in overcoming season-to-season climatic variations.

The study of genotype x environment interaction has been approached in different ways such as the estimation of components of variance, regression, and estimation of stability parameters. A review of these methods is presented in this section. A discussion on the mechanisms and inheritance of stability is also included.

Components of Variance Approach to Genotype x Environment Interactions

The earliest work providing evidence of genotype x environment interaction was reported by Fisher and Mackenzie (1923) in studies of responses of different potato (Solanum tuberosum L.) varieties to manure. This report did not involve the analysis of variance which was introduced later. Sprague and Federer (1951) used the analysis of

variance technique and showed how variance components could be used to separate the effects of genotypes, environments and genotype x environment interaction. This was done by equating the observed mean squares to their expectations and solving the resulting sets of simultaneous equations.

The knowledge of the components of variance can be used to identify stable genotypes. Sprague and Federer (1951) indicated that the interaction variance component for single-cross corn (Zea mays L.) hybrids repeated over locations or years was greater than that for double-cross hybrids. This suggests that double crosses are superior to single crosses for stability of performance. Plaisted and Peterson (1959) evaluated potato varieties over locations in one year and suggested a method of estimating the contribution of a variety to the variety x location components of variance. They analyzed yield data over locations in all combinations of pairs of varieties allowing the estimation of the variety x location components for each analysis of pair of varieties. The contribution of a variety to the variety x location interaction was the average of the components of variance involving that variety. The variety that has the smallest value would be the most stable.

The method has been used to subdivide a growing region in subareas where a genotype would perform consistently better. Horner and Frey (1957) in oats (Avena sativa L.), Liang et al. (1966) in sorghum (Sorghum bicolor (L.) Moench), and Rao (1970) in sorghum concluded that the magnitude of the genotype x location component of variance allows the delimitation of a given region into subregions, thus leading to the choice of stable genotypes to recommend for the different subregions.

The goal of the delimitation is to decrease the genotype x location interaction proportionally to number of subregions compared to the true value for the whole region. The technique also permits the grouping of some locations in order to reduce the magnitude of the mean square for error.

The estimation of the components of variance for variety x location, variety x year, and variety x location x year interactions is helpful in a testing program. Sprague and Federer (1951) estimated the relative magnitude of the variety x location, variety x year, variety x location x year, and error components of variance from a series of top-cross, single-cross, and double-cross yield trials. They suggested that the optimum distribution of a given number of plots would be to have fewer replicates per location and have a large number of locations and years. Obilana and El-Rouby (1980) conducted two-year and three-year sorghum (Sorghum bicolor (L.) Moench) trials in four zones in Nigeria. The authors indicated that the precision of measuring performance of a variety was most effectively improved by increasing the number of years, while increasing the number of replications was the least effective.

Regression Approach to Genotype x Environment Interactions

Many workers observed that the relationship between the performance of different genotypes in various environments and some measure of these environments is linear. There is a genuine underlying relationship between the performance of a genotype and the prevailing environmental conditions, even if the relationship does not always account for all the interactions. The relationship allows the use of regression techniques to characterize the response of genotype to a wide range of environmental conditions. Yates and Cochran (1938) were first to propose the regression

method. This regression technique was not widely known until Finlay and Wilkinson (1963) rediscovered the same method and used it in a tria1 of barley (Hordeum vulgare L.) varieties.

The regression approach includes two parts, an analysis of variance followed by a joint regression analysis to determine whether or not the magnitudes of the genotype x environment interactions are a linear function of the environmental effects. There is no point to proceed to the joint regression analysis uhless the initial analysis clearly shows the significance of genotype x environment interactions. The joint regression analysis is carried out by computing estimates of regression coefficients and partitioning the genotype x environment sums of squares into two parts, one measuring that portion of the genotype x environment interactions which is due to difference among fitted lines, and the other measuring the pooled deviations of the observed values around these fitted lines. The significance of genotype x environment interaction indicates that either or both of these parts will be significant. When differences among regression coefficients are significant, it indicates that each genotype has its own characteristic linear response to change in environment. The significance of pooled deviations indicates either no relationship or no simple relationship exists between the interactions and environmental effects,

The problem in the regression technique is the choice of the measure of the environment. It is highly desirable to measure the environment by something unrelated to the organisms under study to fulfill the basic assumption of independence of the regression analysis. More recently, the use of independent measure of environments has been proposed. Hardwick and Wood (1972) showed how to find a linear function

of a set or environmental variables which can explain better the observed genotype x environment interaction. Perkins (1972) considered the linear function of environmental variables. She estimated the principal component of weather variables and used the functions of the first few components as the predictor. This has a disadvantage because a variable which is not important in determining the response of the genotypes may contribute largely to one or more of the first principal components. Nor and Cady (1979) discussed the use of the average yield of all genotypes in each site as an index of the site productivity and developed a multivariate regression methodology for providing an alternative environmental index independent of the cultivar response. The index is based on the physical measurements of the environments affecting crop yields rather than the environment mean yields. They indicated that with improved measurement techniques and understanding of site variables, the environmental index methodology can be an alternative regression measure of stability and wide adaptability,

The measurement of environmental variables is usually difficult in practice. Freeman and Perkins (1971) concluded that the best measure of the environment is provided by the organisms grown in the environment. Finlay and Wilkinson (1963) and Eberhart and Russell (1966) used the mean of all genotypes grown in the environment, thus violating the assumptions of the regression analysis. Freeman and Perkins (1971) suggested a way of measuring the environment without using the same individuals to determine the environmental effects and the genotype x environmental interaction. They proposed the division of the replicates of the genotypes in two groups, one measuring the environment and the other the genotype x envrronmental interaction. They suggested also the use of genotypes

considered as standards to assess the environment., Jinks and Perkins (l-970) advised the use of parental genotypes as standards when crosses or generations derived from them are under test. Fripp (1972) discussed also the problem of regression of yield of test genotypes on yield of control genotypes. She gave clues for the choice of environmental assessmerit material.. She proposed the use of parental genotypes when their progenies are under test, a single cross when the ecological and physiological behaviors are known and the average mean of all genotypes when the range of environment is large. Nor and Cady (1979) compared the results from regression using environmental variables and those from regression on mean of all genotypes. They found that there was no significant difference between the results. They concluded that the mean of all genotype responses can serve as an environmental assessment without af'fecting the outcome of the regression analysis if the number of genotypes going into the environment mean is large.

The choice of measure of the environment depends on the goal of the experiment, the nature of the material, and the amount of information needed about genotype x environment interaction. The use of environmental variables is statistically more valid than the use of the genotype means.

Stability Parameters

One of the main reasons for testing genotypes in a wide range of environments is to estimate their stability. Many methods have been used to estimate the stability of genotypes.

Finlay and Wilkinson (1963) working with barley varieties developed a dynamic interpretation of varietal adaptation to natural environments. They used the regression technique to compare the performance of

a set of barley varieties grown at several locations for several years. For each variety, a linear regression of an individual variety yield on the mean of all varieties was computed. In order to assess or measure an environment, the mean of all varieties grown in the environment was used. The assessment allows the grading of the environments from the lowest yielding to the highest yielding. To induce the homogeneity of error variance and a high degree of linearity in the regression of individual genotype yield on environmental yield, all calculations were performed on logarithmic scale.

The coefficient of regression (b) and the mean yield over all environments were used to classify the varieties for stability. They concluded that a variety with b = 1 has average stability. A variety with b = 1 and above average yield was considered having general adaptation, while a variety with b = 1 and below average yield was classified as poorly adapted to all environments.

Furthermore, b > 1 describes a variety with increasing sensitivity to environmental changes, thus has lower stability and greater adaptability to high yielding environments. Regression coefficient les5 than 1.00 describes a variety with greater resistance to environmental changes, therefore, it has above average stability and specific adaptability to low yielding environments.

Finlay and Wilkinson (1963) concluded that stability was defined by the regression coefficient, while adaptability was defined by the relative mean yield of the variety.

The form combined analysis of variance was as follows:

Table 1. Form of the analysis of variance in Finlay and Wilkinson (1963) method.

Source	df
Genotype	g - 1
Environment	e - l
Genotype x Environment	(g-l) (e - 1)
Regressions	g - 1
Deviations	(g - l) (e - 2)
Replicates Within Environments	e(r - 1)
Residual	e(r - 1) (g - 1)

They suggested the plotting of variety mean yield against the regression coefficient for the selection of a variety with general adaptability and good stability.

Eberhart and Russell (1966) proposed a mode1 which defines the stability parameters

$$Y_{ij} = u_i + \beta_i I_j + \delta_{ij}$$

Y_{ij} = mean of the ith variety at the jth environment.

u_1 = mean of the ith variety over all environments.

β_i = regression coefficient.

I_j = environmental index obtained as the mean of all varieties at the jth environment minus the grand mean.

δ_{ij} = deviation from regression of the ith variety at the jth environment.

The mode1 partitioned the genotype x environment interaction in each variety into variation due to the response of the variety to

environmental indices and unpredictable deviations from regression on the environmental indexes.

Eberhart and Russell (1966) used the mean yield of all varieties in an environment to assess the yield potential in that environment.

The regression coefficient (b) and the deviations from regression were considered to describe the performance of a variety over a series of environments. The regression coefficient measures the average increase of response of a variety per unit increase of an environmental index. The deviations from regression measure the agreement between predicted and observed responses.

The performance of a variety can be predicted by the eyuation

$$Y_{ij} = \bar{X}_i + b_i I_j, \text{ where } \bar{X}_i = \text{estimate of } u_i.$$

The authors defined a stable variety *as* a variety with b = 1 and deviations from regression as small as possible. Regression coefficient less than 1.00 indicates a variety lacking the ability to respond well to favorable conditions (does better in unfavorable conditions). Regression coefficient greater than 1.00 indicates a variety with the ability to respond to favorable conditions.

The components of variance have been partitioned in a more detailed way than in Finlay and Wilkinson (1963). The analysis of variance is as follows:

Table 2. Form of analysis of variance when stability parameters are estimated according to Eberhart and Russell (1966).

Source	df	Sum of squares	Mean squares
Total	nv-1	$\Sigma\Sigma Y_{ij}^2$ - CE	
Variety	v-1	$1/n\Sigma Y_{i.}^2$ - CF	MS_1
Environment (E)	*n-1*		
Variety x Environment	v(n-1) (v-1) (n-1)	$\Sigma\Sigma_{ij}^2 - \Sigma_{i.}^2/n$	
Environment (linear)	1	$1/v(\Sigma Y_{.j} I_j)^2/\Sigma I_j^2$	
Variety x E(linear)	v-1	$\Sigma_i[(\Sigma_j Y_{ij} I_j)^2/\Sigma I_j^2]$ -E(linear)S.S.	MS_2
Pooled deviations	V(n-2)	$\Sigma\Sigma\delta_{ij}^2$	M_3
Variety 1	n-2		
.			
.			
.			
Variety v	n-2		
Pooled error	n(r-1)(v-1)		MS

The deviations from regression appeared to be the most important parameter for the selection of stable varieties. A desirable variety will have a b close to 1, a non-significant deviation from regression, and a mean yield above the mean yield of all varieties.

The authors concluded that a good estimate of the coefficient of regression can be obtained from a few environments if they cover the

range of expected responses. However, since the variance of S_d^2 is a function of the number of environments, several environments with maximum replications per environment are necessary to estimate reliably the deviations from regression.

There was some disagreement on the use of the regression coefficient and deviation from regression in defining stability. Finlay and Wilkinson (1963) considered the regression coefficient as the best measure of adaptability. Breese (1969) also suggested the use of the regression coefficient to decide on the relative adaptability. He used the mean to discriminate between genotype with equal b values or specific performance within a limited set of environments. Joppa et al. (1971) concluded that the regression was the best indicator of general stability. Miezan et al. (1979) pointed out that the use of the regression coefficient as stability parameter would be inappropriate if there exists covariance among genotypes. The assumption of zero covariance could be satisfied if the genotypes represent a random sample from a finite population.

Mallana et al. (1982) felt that the deviation from regression was more appropriate to characterize a genotype. Ram et al. (1978) found that the largest proportion of the genotype x environment interaction was accounted for by the linear component. Since the regression coefficient of a genotype is a function of the other genotypes, they stated that the deviations from regression was a more reliable estimated stability. Eberhart and Russell (1969) used both the regression coefficient and the deviations from regression to describe stability of performance over environments but concluded that the most important stability parameter was the deviations from regression.

In addition to the Finlay and Wilkinson (1963) and Eberhart and Russell (1969) methods, other methods have been used to study the stability of performance. Lewis (1965) defined the stability factor (S.F.) which measures the phenotype stability of an individual genotype

$$S.F. = \frac{\bar{X}\ HE}{\bar{X}\ LE} .$$

$\bar{X}$ HE = mean of the genotype in the high yielding environmcnt.

$\bar{X}$ LE = mean of the genotype in the low yielding environment.

The maximum phenotypic stability is characterized by S.F. = 1. The greater S.F. deviates from unity the less stable is the phenotype.

Wricke (1962) proposed a stability parameter called ecovalence which is the contribution of a genotype to GE interaction sum square. The GE interaction sum square is partitioned into individual sum squares.

$$W_j = \Sigma(\bar{Y}_{ij} - Y_{.1} - \bar{Y}_{.3} + Y\ ...)^2$$

W_j = the contribution of the jth variety to the G x E interaction sum square.

Shukla (1972) defined the stability variance σ_I^2 for a genotype which represents the contribution of each genotype to genotype-environment interaction sum square. He proposed an approximative F-test, the ratio of σ_I^2 to the pooled error. The difference in magnitude indicates the variation in degree of stability.

Pinthus (1973) and Langer et al. (1979) proposed the use of the coefficient of determination (r^2), which measures the proportion of the variety's production variation that is attributable to the linear model, as an index of production stability. Langer et al. (1979) also found a useful method in preliminary trials in oat varieties based on indices

related to the range in productivity. The first index is Rl which is the difference between the maximum and minimum yields of a variety in a series of environments; the second, R_2, is the difference between yield of a variety in the lowest and highest yielding environments. Francis and Kannenberg (1978) suggested a method of grouping genotypes based on the mean yields and the mean coefficient of variation in maize. The genotypic group with a high mean yield and small variation was considered stable.

Frasad and Singh (1980) comparing the Lewis method to the regression analysis found the former as effective as the latter to measure stability. Langer et al. (1979) found a high and significant correlation between the ecovalence coefficient (W), the deviation from regression (Sd), and the coefficient of determination (r^2). This indicates that any one of the parameters should be satisfactory for measuring stability.

Luthra (1974) studied 18 varieties of wheat in 24 environments over two years. The rank correlation between the ecovalence and the Eberhart and Russell methods was low. It. was observed that the most stable genotypes can be detected by usinç any of the stability methods. Because of a computational convenience, the Lewis method, ecovalence method, and the coefficient of determination should be suggested for prediction of responsiveness and stability.

Mechanisms and Inheritance of Stability

To deal better with the selection of stable genotypes in a breeding program, it is necessary to know the mechanisms promoting the stability of performance. Generally a plant breeder prefers to produce a genotype with as broad an adaptation as possible. That means a

genotype which can adjust to the environment such that it consistently gives relatively high yield is called well buffered (Allard and Bradshaw, 1964).

Allard and Bradshaw (1964) described two ways in which a genotype may achieve stability depending on the genetic constitution. The first is individual buffering. In this case, all individuals in the population are adapted to a series of environments, thus producing acceptable yields of the variety. The second is populational buffering which is based on the heterogeneity among individuals composing the population. Each individual is adapted to a different range of environments promoting a compensation effect in the population in response to these environments. This means that a population possesses a number of adapted individuals such that some individuals perform better in a given environment and compensate for the reduction in yield of less adapted individuals.

The achievement of stability also may depend on some morphological and physiological changes. Heinrich (1981) concluded in his study on sorghum in Nebraska that yield stability is primarily related to tolerance to stress in all growth stages. He suggested that the best way to improve stability is through breeding for stress tolerance. He stated that yield stability mechanisms should be identifiable, heritable, and combinable with yield potential.

Concerning these promoting mechanisms, many authors support the idea that the level of diversity is related to stability of performance. Jensen (1952) found in oat varieties that multilines possessed greater stability of performance and broader adaptation to varying environments as compared to pure lines. Jones (1958) evaluated corn double crosses

and single crosses. The comparison of the coefficients of variability showed that the double crosses had smaller coefficients of variability (12.3%) than single crosses (21.4%). He attributed the differences in variability to the buffering effects due to heterogeneity in the double crosses. Allard (1961) worked with 10 lima bean (Phaseolus lunatus L.) populations representing three different levels of diversity (pure lines, mixtures, and bulks). He found that productivity was not related to diversity. Pure lines outyielded the mixtures and the bulk populations, but the calculation of the variance components showed that the pure lines had larger variance than the bulks and the mixtures. This indicates that bulks and mixtures of pure lines perform more consistently than the pure lines grown individually. The bulks and the mixtures were more or less equal in ability to main consistent yield in different environments.

Rowe and Andrew (1964) conducted a multilocation tria1 of corn varieties composed of inbred lines and F_1 hybrids. They found some difference in response to envîronmsntal changes due to difference in ability to exploit favorable environments. The segregating groups showed more stability than the inbred lines and the F_1 groups. The superiority of the segregating populations is due to the compensation interaction among individuals within each group.

Rasmusson (1968) tested homogeneous varieties of barley, simple mechanical mixtures, and bulk hybrids. There was no difference between homogeneous varieties and the simplte mixtures, but these both were less stable than the bulk hybrîds. Because of a large difference among individuals of the same group, no definite conclusion about the ranking can be done.

Reich and Atkins (1970) comparing parental lines of sorghum, F_1 hybrids, and hybrid blends remarked that the hybrid blends yielded consistently better. Collectively, the heterogeneous populations yielded 102% of the mean of their homogeneous components. Jowett (1972) showed that a three-way cross was more stable than a singie cross when the deviation from regression was used as the stability critecion. When the regression coefficient was used, the single cross was as stable as the three-way cross.

Along with others, Sprague and Federer (1958) agreed on the superiority of heterogeneous populations in stability. Because of that, Schilling et al. (1983) suggested the use of multilines in peanut (Arachis hypogaea L.) to reduce genotype x environment interaction.

Despite some convincing results, there is still some disagreement about the relationship between heterogeneity and stability. Schilling et al. (1983) found peanut lines as stable as multilines. Jowett (1972) indicated in his study on sorghum that a single cross showed lower deviation from regression than the three-way cross. Therefore, stability can be attained either with a narrow based population or a broad based population (Scott, 1967). This indicates that stability is under genetic control. Thus, selectian for stability is possible. Scott (1967) defined two types of stability which can be selected for. The first is a genotype which exhibits the least yield variability over all test environments. The second is the selection of a genotype which maintains its relative performance compared to the others tested in many environments. These two stabilities are mutually exclusive. He suggested the first method as useful for selection to drought conditions, but the selection for the first type of stability is related to low

yields in favorable growing conditions. On the other hand, in favorable conditions, it is better to select for the second type of stability.

The fact that selection for level of stability or for stability is effective emphasizes the importance of the inheritance of the character. Bush et al. (1976) indicated that stability in wheat (Triticum aestivum L.) genotypes as measured from regression coefficients may be simply inherited and predicted from parental line stability. Patanothai and Atkins (1974) found the response of sorghum lines and hybrids to be largely controlled by additive gene effects, but the inheritance of the deviations from regression was found to be very complex. Eberhart and Russell (1969) found all types of gene action to be involved in the inheritance of the deviations from regression in maize.

This indicates that the inheritance of stability needs to be better investigated. Nothing is known concerning the number of genes conditioning the stability of yield (Scott, 1967). The mode of inheritance seems to vary from crop ta crop and as a function of external factors.

MATERIALS AND METHODS

Description of the Trials

The study was conducted with 18 genotypes (Table 3) coming from the crosses of 6 females and 3 males. Each male was crossed to each female. The female lines Si-1049 through 81-1163 were derived from selections of PI 185642, an early large-seeded genotype introduced from Ghana. They vary in number of backcrosses to the A_1 cytoplasm of Tift $23DA_1$.

The genotypes were planted at three locations in Nebraska and one location in Kansas in 1983. Two trials (irrigated and non-irrigated) were planted at each location. The irrigation treatments were applied before and after bloom. The amounts of water applied in the irrigated trials were not recorded. In Nebraska, the trials were conducted at the University of Nebraska Agricultural Field Laboratory, Mead, the High Plains Agricultural Laboratory, Sidney, and the Agricultural Research Station, Clay Center. The Kansas location was the Fort Hays Branch Agricultural Experiment Station, Hays.

The soil at Mead was Sharpsburg silt clay loam. Trials at Sidney were on a Keith silty loam. At Clay Center, the trials were on a Hastings silty loam. At Hays, the two trials were planted on different soils. The irrigated tria1 was on a Roxbury silt loam, while the non-irrigated tria1 was on a Crete silty clay loam.

The altitude at Mead is 350 m. It is 1800 m at Sidney, 543 m at Clay Center, and 579 m at Hays.

Table 3. List of the 18 hybrids used in the trials in 1983.

Hybrid	Crosses			Female number	Male number	Pedigree	
	Female series number		Male series number			Female	Male
1	81-1049	x	78-7088	1	1	PI185642D$_2$A$_1$	T239DB$_2$/4*Serere 3A
2	81-1056	x	78-7088	2	1	"	"
3	81-1083	x	78-7088	3	1	"	"
4	81-1088	x	78-7088	4	1	"	"
5	81-1163	x	78-7088	5	1	"	"
6	82-2355	x	78-7088	6	1	Tift 23D$_2$A$_1$E	
7	81-1049	x	79-1137	1	2	PI185642D$_2$A$_1$	PI286998/2/PI185642/Tift 23D$_2$B$_1$
8	81-1056	x	79-1137	2	2	"	"
9	81-1083	x	79-1137	3	2	"	"
10	81-1088	x	79-1137	4	2	"	"
11	81-1163	x	79-1137	5	2	"	"
12	82-2355	x	79-1137	6	2	Tift 23D$_2$A$_1$E	
13	81-1049	x	79-4104	1	3	PI18564D$_2$A$_1$	PI287049/PI185642/2/PI287049/Tift 23D$_2$B$_1$
14	81-1056	x	79-4104	2	3	"	"
15	81-1083	x	79-4104	3	3	"	"
16	81-1088	x	79-4104	4	3	"	"
17	81-1163	x	79-4104	5	3	"	"
18	82-2355	x	79-4104	6	3	Tift 23D$_2$A$_1$E	

All trials received normal. land preparation. The genotypes were evaluated in a randomized block design with four replications. Some plots were flooded in the irrigated tria1 at Clay Center. For planting, a four-row cone planter pulled by a John Deere tractor was used. The entries were planted in single-row plots with 76 cm between rows. All trials received pre-emergence applications of herbicide (Miloguard). Except the trials at Hays, no trials received fertilizers. At Hays, nitrogen fertilizer was applied in the non-irrigated tria1 at the rate of 45 kg/ha and in the irrigated tria1 at the rate of 30 kg/ha. All the trials were over-seeded, then thinned to nine plants per meter. The trials were hand weeded.

The plots were trimmed ta 5 m. Later on, the plots were remeasured before harvest in all trials.

The planting date for each tria1 is given in Table 4. Rainfall and temperature data (Table 5) were recorded for all locations.

Plot Eleasurement

Before harvesting, data were collected from each plot in all trials, and the following data were taken:

1. Days to half bloom, determined by the number of days from pianting to flowering date, recorded when 50% of the plants in the plot had reached half bloom on the main tiller.
2. Plant height, taken from the ground level to the top of the plants in the plots.
3. Row lengths, measured for each plot.

Table 4. List of trials used in the study (1983).

Location	Agronomic Treatment	Planting Date
Nebraska		
Mead	No irrigation	June 3
Mead	Irrigation	June 3
Sidney	No irrigation	June 10
Sidney	Irrigation	June 10
Clay Center	No irrigation	June 6
Clay Center	Irrigation	June 6
Kansas		
Hays	No irrigation	June 17
Hays	Irrigation	June 16

Table 5. Climatic data of locations where the trials were conducted in the 1983 growing season.

Location	Average temperature	Total precipitation
Mead, NE	22.7	28.8
Sidney, NE	19.8	3.8
Clay Center, NE	21.8	31.1
Fort Hays, KS	25.3	11.9

Growing season: June-September.

The plots were harvested after all genotypes had reached maturity. The irrigated tria1 in Hays, the non-irrigated in Mead, and the two trials in Sidney were harvested and threshed by combine. The remaining trials were hand-harvested and threshed by combine. After threshing the grain from each plot was cleaned and then tested for moisture percentage in a Burrows digital moisture computer 700. A subsample of each plot was taken to determine the 100-seed weight.

Plot grain weight was determined.

From the data taken after harvesting, the following variables were calculated.

1. Seeds/m^2: number of seeds per square meter was computed as [(Grain weight/plot ÷ plot size) ÷ (100-seed weight)] x 100.

   Plot size (m^2) = Row length x 0.76 m.

2. Grain yield/ha (kg/ha).

Statistical Procedures

The irrigation treatment used in this study differed from location to location. Thus, environments were considered as nested within location. The genotypes in this study are considered fixed effects. The locations and environments were considered as random.

The analysis of this experiment was subdivided in the following steps:

a. Individual Experiment Analysis of Variance

The objective of this analysis was to determine the error mean square for each trial. The error mean squares were tested by the

Bartlett test of homogeneity of variance. They were used to calculate the pooled error mean square for the combined analyses and the stability analysis.

The following mode1 was used for an individual trial:

$$P_{ijk} = u_i + r_{ij} + g_{ik} + e_{ijk}$$

where:

P_{ijk} = observation of the k^{th} genotype in the j^{th} replication in the i^{th} experiment.

u_i = general mean of the i^{th} experiment.

r_{ij} = effect of the j^{th} replication in the i^{th} experiment.

g_{ik} = effect of the k^{th} genotype in the i^{th} experiment.

e_{ijk} = random error associated with observation of the k^{th} genotype in the j^{th} replication in the i^{th} environment.

The appropriate analysis of variance is given in Table 6.

b. Combined Analysis

This was computed from the unweighted genotype means as suggested by Cochran and Cox (1957). The combined analysis provides more information about the genotype x environment interaction which cannot be obtained from the individual environment analysis. It was computed over replications.

The following mode1 was used:

$$\bar{P}_{ijk} = u + l_i + e(l)_{ji} + g_k + (gl)_{ki} + (ge(l))_{kji} + \bar{e}_{ijk}$$

Table 6. Form of analysis of variance for an individual environment.

Source	df
Replication	r - 1
Genotype	g - 1
Error	(r-1)(g-1)

r = number of replications in each experiment.

g = number of genotypes.

where:

$\bar{P}_{ijk}$ = mean of the k^{th} genotype in the j^{th} environment in the location.

u = general mean of the experiments.

l_i = effect of the i^{th} location.

$e(l)_{ji}$ = effect of the j^{th} environment within the i^{th} location.

g_k = effect of the k^{th} genotype.

$(gl)_{ki}$ = interaction effect of the k^{th} genotype with the i^{th} location.

$(ge(l))_{kji}$ = interaction effect of the k^{th} genotype with j^{th} environment in the i^{th} location.

$\ddot{e}_{ijk}$ = random error associated with the k^{th} genotype mean at the j^{th} environment in the i^{th} year.

The appropriate form of analysis of variance is given in Table 7. The components of variance for the interaction effects along with their standard errors were also calculated as follows:

Components of variance:

$$\hat{\sigma}^2 ge/l = M_2 - M_1$$

$$\hat{\sigma}^2 gl = (M_3 - M_2)/e$$

Standard errors:

$$S.E.\ (\hat{\sigma}^2 ge/l) = \left[\frac{2M^2_2}{(df_2 + 2)} + \frac{2M^2_1}{(df_1 + 2)}\right]^{\frac{1}{2}}$$

Table 7. Form of the combined analysis of variance.

Source	df	Mean square		F
		Observed	Expected	
Location (L)	l-1			
Environment within location (E/L)	$\sum_{i=1}^{l}(e_i-1)$			
Genotypes (G)	g-1	M_4	$\sigma^2_{e/n} + \sigma^2_{ge/l} + e\sigma^2_{ge} + \frac{el\sum(g_k-\bar{g})^2}{(g-1)}$	M_4/M_3
G x L	(g-1)(l-1)	M_3	$\sigma^2_{e/n} + \sigma^2_{ge/l} + e\sigma^2_{gl}$	M_3/M_2
G x E/L	$(g-1)\sum_{i=1}^{l}(e_i-1)$	M_2	$\sigma^2_{e/n} + \sigma^2_{ge/l}$	M_2/M_1
Pooled error	$(g-1)\sum_{i=1}^{P}(r_i-1)$	M_1	$\sigma^2_{e/n}$	

l = number of locations.
e = number of environments within locations.
n = harmonic mean of the number of replications.
e = number of genotype.
r = number of replications per experiment.
P = number of experiments.

$$n = P/\Sigma(1/ri)$$

where:

P = number of experiments.

r_1 = number of replications in the i^{th} experiments.

+ The pooled error mean square for the combined analysis was calculated from the formula:

$$\text{Pooled error mean square} = \frac{1}{P}\Sigma S_i^2/r_i$$

where:

P = number of experiments.

S_i^2 = error mean square of the i^{th} experiment.

r_i = number of replications in the i^{th} experiment.

$$S.E.\ (\hat{\sigma}^2_{gl}) = 1/e\left[\frac{2M^2_3}{(df_3 + 2)} + \frac{2M^2_2}{(df_2 + 2)}\right]^{\frac{1}{2}}$$

c. Stability Analysis

The stability analysis was done using the Eberhart and Russell (1966) model. The regression of each genotype mean on the enviromental index and the deviation from regression were used to measure stability. The stability parameters were computed for yield and yield components of each genotype. The appropriate form of analysis of variance is given in Table 2.

The hypothesis that there are no genetic differences among genotypes for their regression on environmental indices.

$$H_o = \beta_1, = \beta_2 = \cdot\ \cdot\ \cdot\ \cdot\ \cdot = \beta_g$$

was tested by $F = M_2/M_3$.

The hypothesis that any regression coefficient does not differ from unity was tested by the appropriate t-test.

The significance of the deviations mean squares was tested using the pooled error as the denominator in the F-test..

d. Correlations

Correlations between mean grain yield and stability parameters for yield were computed over the environment. The correlations between stability for yield and stability for yield components were also calculated.

All these analyses were done on the Nebraska University Remote Operating Station (N.U.R.O.S.) at the University of Nebraska, Lincoln, using S.A.S.[1] The analyses of variance for the individual experiments were done with the GLM procedure and for the combined analysis over environments with PROC ANOVA. The regression analysis was done with the PROC REG procedure and the correlations with PROC CORR procedure.

[1] Statistical Analysis System. Description available from SAS Institute, Inc., Box 8000, Cary, North Carolina 27511.

RESULTS

The environment mean yield for all hybrids ranged from 464 kg/ha in Hays (non-irrigated) to 3333 kg/ha in Clay Center (irrigated) (Table 8). Mean days to 50% bloom ranged from 60 days to 71 days, mean plant height from 81.6 cm to 127.6 cm, mean 100-seed weight from 0.88 g to 1.24 g, and mean number of seeds from 4828 to 26,329 (Table 8).

The average growing season temperatures ranged from 19.8°C at Sidney to 25.3°C at Hays and the total growing season moisture received from 3.8 cm in Sidney to 31.1 cm in Clay Center (Table 5).

The diversity among environment means and the range in environmental factors provided a good opportunity to study for genotype x environment interactions and stability.

Genotype x Environment Interaction

The combined analysis considered the variation due to hybrid, hybrid x location, and hybrid x environment within location. The components of variance for each of the above effects were estimated from the combined analysis to assess the importance of the different interactions.

The combined analysis of variance (Table 9) shows a significant difference among the means of the hybrids for days to 50% bloom plant and height and seeds/m^2. The hybrid means for seed weight were not significantly different. The comparisons among means (Table 14) showed a difference in seed weight among the hybrids.

Table 8. Environment means for the different traits.

Location	Environment	Trait				
		Days to 50% bloom	Plant height	100-seed weight	Seeds/m^2	Grain Yield
		(days)	(cm)	(g)	(number)	(kg/ha)
Mead	non-irrigated	62.7	112.4	1.13	10,126	1,208
	irrigated	63.4	127.6	1.24	21,245	2,777
Sidney	non-irrigated	68.5	107.7	1.04	16,479	1,784
	irrigated	[illegible]	[illegible]	0.99	16,756	1,713
Clay Center	non-irrigated	63.0	106.1	1.19	20,111	2,522
	irrigated	64.5	123.4	1.21	26,329	3,333
Hays	non-irrigated	70.5	81.6	0.88	4,828	464
	irrigated	59.8	125.1	1.07	25,340	2,801

Table 9. Combined analysis of variance for the 18 millet hybrids.

Source	df	Mean square				
		Days to 50% bloom	Plant height	100-seed weight	Seeds/m^2	Grain yield
		(days)	(cm)	(g)	(number)	(kg/ha)
Location (L)	3	202.57	1,942.65	0.4962	510,467,188	12,443,137
Environment/ location (E/L)	4	266.00	5,446.39	0.1128	1,311,979,117	19,314,089
Hybrid (H)	17	19.08**	183.17**	0.0965	15,559,106*	576,694**
H x L	51	1.99**	26.25**	0.0028	8,017,627	93,921*
H x E/L	68	0.92	14.23	0.0029*	5,741,791	59,681
Pooled error	394	1.02	11.30	0.0020	5,172,520	65,845

* and ** indicate significance at the 0.05 and 0.01 levels, respectively.

The hybrid x location mean square indicated significant differences for grain yield (0.05 level), plant height, and days to 50% bloom (0.01 level). The differences among hybrids were consistent for 100-seed weight and seeds/m^2 across locations.

The hybrid x environment within location mean squares were significant (0.05 level) for 100-seed weight. For the other traits, the differences among hybrids were consistent across environment within location.

The magnitude of the components of variance gives information about the importance of the different interactions. The estimates of the components of variance for all traits are given in Table 10. For days to 50% bloom, the component of variance of hybrid x location was higher than for hybrid x environment within location. The same pattern also was found for plant height, grain yield, and seeds/m^2. The results showed that for grain yield and days to 50% bloom, the estimate of $\hat{\sigma}^2_{HE/L}$ was negative and less than the S.E., and thus it can be considered equal to zero. The component of variance for hybrid x environment within location was higher for 100-seed weight.

Stability Analysis

The stability anaiysis was performed with all hybrids over the eight environments. It provides an estimate of the linear regression (b) and mean square deviations from regression (S^2_d) for each hybrid.

Stability Analysis of Variance

The results in Table 11 show that hybrid x environment interaction was significant for all traits except grain yield.

Table 10. Estimates of the components of variance for hybrid x environment within location ($\hat{\sigma}^2_{HE/L}$) and hybrid x location ($\hat{\sigma}^2_{HL}$) from the combined analysis.

Variance component	50% bloom	Plant height	100-seed weight	Seeds/m^2	Grain/yield
	(days)	(cm)	(g)	(number)	(kg/ha)
$\hat{\sigma}^2_{HE/L}$	-0.10 ± 0.17	3.03 ± 2.55	0.0009 ± 0.0005	569,271 ± 1,037,821	-6,164 ± 11,120
$\hat{\sigma}^2_{HL}$	0.57 ± 0.21	5.96 ± 2.82	-0.00005 ± 0.030	1,137,918 ± 917,565	17,120 ± 10,424

Table 11. Stability analysis of variance for the 18 millet hybrids.

Source	df	Mean square				
		Days to 50% bloom	Plant height	100-seed weight	Seeds/m^2	Grain Yield
		(days)	(cm)	(g)	(number)	(kg/ha)
Hybrid x Environment	119	1.38**	19.44**	0.0028""	6,717,149*	74,356
Environment (linear)	1	1,671.74	27,613.51	193.99	6,779,318,036	114,552,768
Hybrid x Environment (linear)	17	1.70	30.32**	0.0075*	8,307,957	85,848
Pooled deviations	108	1.25	16.64**	0.0020	6,093,565	68,414
Pooled error	394	1.02	11.30	0.0020	5,172,520	65,845

* and ** indicate significance at the 0.05 and 0.01 levels, respectively.

The hybrid x environment (linear) was significant for plant height and 100-seed weight at the 0.05 level indicating that there were genetic differences among hybrids for their regression coefficients. For days to 50% bloom, seeds/m^2, and yield, there was no evidence of genetic differences for the regression coefficients.

The pooled deviations were significantly different from the pooled error for plant height. The hybrids showed a non-linear response to environments for plant height.

Stability Parameters

1) Days to 50% bloom (Table 12):

Thirteen out of the 18 hybrids were stable for days to 50% bloom with b not significantly different from 1.00 and mean square deviations not significantly different from 0. Hybrid 17, which was one of the earliest, appeared to be the most unstable. Hybrid 11, which flowered in 65 days, was the most stable.

2) Plant height (Table 13):

Twelve hybrids had b values not significantly different from 1.00 and mean square deviations not significantly different from 0 and stable. Hybrids 3, 4, 7, and 11 were the most stable for plant height. The most unstable of the 18 hybrids was hybrid 12 with both b and deviation mean square significantly different from 1.00 and 0, respectively.

Table 13. Stability parameters of the 18 hybrids for days to 50% bloom.

Hybrid	Mean	b†	MSD††	R^2	
	(days)				
1	63.4 h	0.98	0.95	0.94	s
2	65.6 cde	1.03	0.72	0.96	s
3	64.8 ef	1.07	0.93	0.93	s
4	64.0 fgh	1.22	0.98	0.83	
5	63.3 hi	1.01	1.23	0.75	s
6	62.3 i	0.92	0.41.	0.92	s
7	66.1 cd	1.00	2.76	0.91	s
8	69.4 a	0.71**	1.68	0.92	
9	66.2 bcd	1.15	0.42	0.92	s
10	67.2 b	0.98	1.52	0.97	s
11	64.9 ef	0.97	0.38	0.89	s
12	66.6 bc	0.83	3.48**	0.97	
13	65.3 de	1.23*	0.74	0.87	
14	66.3 bcd	1.09	0.56	0.96	s
15	65.3 de	1.00	1.44	0.88	s
16	64.6 efg	1.06	0.40	0.95	s
17	63.6 gh	0.78*	2.20"	0.45	
18	64.1 fgh	0.96	1.78	0.84	s
Mean	65.17				

Means followed by the same letter are not significantly different at the 0.50 level.

† * and ** indicate significant difference from 1.00 at the 0.05 and 0.01 levels, respectively.

†† * and ** indicate significant difference from 0 of the 0.05 and 0.01 levels, respectively.

s = Stable. A stable hybrid is the one with b not significantly different from 1.00 and mean square deviations (MSD) not significantly different from 0.

Table 13. Stability parameters of the 18 hybrids for plant height.

Hybrid	Mean		b†	MSD††	R^2	
	(cm)					
1	111.10	def	0.94	15.20	0.93	s
2	111.57	de	1.13	25.98"	0.92	
3	113.06	cd	0.97	9.88	0.96	s
4	110.63	dcf	1.00	9.09	0.96	s
5	108.51	efg	0.84	16.02	0.92	s
6	118.06	b	1.19	24.16*	0.94	
7	116.06	bc	0.97	8.89	0.96	s
8	113.51	cd	1.23*	14.56	0.96	
9	117.52	b	0.96	12.04	0.95	s
10	112.22	de	1.03	2.76	0.99	s
11	111.44	de	0.92	9.84	0.96	s
12	121.62	a	1.34**	34.39**	0.93	
13	107.51	fgh	1.04	13.21	0.95	s
14	106.77	gh	0.86	24.69*	0.88	
15	106.16	gh	0.93	17.06	0.93	s
16	104.69	h	0.96	21.99	0.91	s
17	104.71	h	0.79*	27.55*	0.85	
18	113.16	cd	0.92	12.29	0.95	s
Mean	111.57					

Means followed by the same letter are not significantly different at the 0.05 level.

†* and ** indicate significant difference from 1.00 at the 0.05 and 0.01 levels, respectively.

††* and ** indicate significant difference from 0 at the 0.05 and 0.01 levels, respectively.

s = Stable. A stable hybrid is the one with b not significantly different from 1.00 and mean square deviations (MSD) not significantly different from 0.

3) 100-seed weight (Table 14):

Seven hybrids (2, 3, 4, 5, 8, 13, 17) were unstable (Table 14). Four stable hybrids (1, 7, 9, and 11) had mean 100-seed weight higher than the average mean 100-seed weight of 1.10 g over all hybrids. As such, these were considered the desirable hybrids for seed weight. Hybrid 2 (b = 1.40 significantly higher than 1.00) had a mean 100-seed weight of 1.25 performed better in favorable conditions. Hybrid 17 (b = 0.35) was expected to exceed average performance in unfavorable conditions.

4) Seeds/m^2 (Table 15):

Fifteen hybrids had a regression coefficient not significantly different from 1.00 and mean square deviations were not significantly different from 0. They were stable (Table 15). Hybrids 3, 5, 7, 9, 11, and 17 had mean seeds/m^2 hiqher than the average mean seeds/m^2 of 17,652 over all hybrids. They were considered desirable hybrids for seeds/m^2. Hybrid 18 produced an average seeds/m^2 of 18,914 and b value of 1.33 (significantly higher than 1.00) indicating that it performed better in favorable conditions. Hybrid 2 had a b value of 0.74 (significantly lower than 1.00) indicatinq it did better in unfavorable conditions.

5) Grain yield/ha (Table 16):

The regression coefficients ranged from 0.72 to 1.18 and mean grain yield from 1,575 kg/ha to 2,489 kg/ha. Fifteen hybrids showed stability for grain yield with a regression coefficient not significantly different from 1.00 and mean square deviations not significantly

Table 14. Stability parameters of the 18 hybrids for 100-seed weight.

Wybrid	Mean	b†	MSD††	R^2	
	(g)				
1	1.26 a	1.17	0.0023	0.91	s
2	1.25 a	1.40**	0.0016	0.96	
3	1.24 a	1.32*	0.0025	0.93	
4	1.19 b	1.14	0.0046"	0.83	
5	1.19 b	0.73	0.0031	0.75	
6	0.97 g	0.93	0.0013	0.92	s
7	1.11 cde	0.96	0.0017	0.91	s
8	1.09 cde	1.36**	0.0029	0.92	
9	1.12 cd	0.90	0.0012	0.92	s
10	1.03 f	1.15	0.0008	0.97	s
11	1.12 cd	0.77	0.0013	0.89	s
12	0.88 h	1.11	0.0007	0.97	s
13	1.07 def	1.18	0.0046*	0.85	
14	1.09 cde	1.01	0.0008	0.96	s
15	1.07 def	0.83	0.0016	0.88	s
16	1.07 def	0.89	0.0007	0.95	s
17	1.12 cde	0.35**	0.0027	0.45	
18	0.87 h	0.76	0.0019	0.84	s
Mean	1.10				

Means followed by the same letter are not significantly different at the 0.05 level.

†* and ** indicate significant difference from 1.00 at the 0.05 and 0.01 levels, respectively.

††* and ** indicate significant difference from 0 at the 0.05 and 0.01. levels, respectively.

s = Stable. A stable hybrid is the one with b not significantly different from 1.00 and mean square deviations **(MSD)** not significantly different from 0.

Table 15. Stability parameters of the 18 hybrids for seeds/m^2.

Hybrid	Mean		b†	MSD††	R^2	
	(number)					
1	16,213	def	0.88	7,199,502	0.87	s
2	18,312	bcde	0.74*	12,193,275*	0.74	
3	18,758	abcd	0.85	2,696,626	0.94	s
4	17,178	abcdef	1.02	3,261,607	0.95	s
5	19,277	ab	1.15	2,458,368	0.98	s
6	19,614	a	1.21	13,016,728*	0.87	
7	18,365	abcde	1.09	1,371,689	0.98	s
8	15,995	ef	0.95	7,985,705	0.88	s
9	19,029	abc	0.99	5,717,384	0.91	s
10	16,179	def	0.95	6,235,044	0.90	s
11	18,780	abcd	1.18	1,079,601	0.99	s
12	16,706	bcdef	0.91	5,563,814	0.90	s
13	15,927	ef	0.93	1,923,816	0.96	s
14	16,565	cdef	0.85	2,505,620	0.95	s
15	17,541	abcdef	0.90	8,888,717	0.85	s
16	15,328	f	0.97	1,113,809	0.98	s
17	19,056	abc	1.07	4,917,419	0.94	s
18	18,914	abc	1.33**	21,555,525**	0.84	
Mean	17,652					

Means followed by the same letter are not significantly different at the 0.05 level.

†* and ** indicate significant difference from 1.0 at the 0.05 and 0.01 levels, respectively.

††* and ** indicate significant difference from 0 at the 0.05 and 0.01 levels, respectively.

s = Stable. A stable hybrid is the one with b not significantly different from 1.00 and mean square deviations (MSD) not significantly different from 1.

Table 16. Stability parameters of the 18 hybrids for grain yield.

Hybrid	Mean	b†	MSD††	R^2	
	(kg/ha)				
1	2,182 bcd	1.03	88,216	0.93	s
2	2,483 a	0.99	220,140**	0.83	
3	2,489 a	1.06	48,051	0.96	s
4	2,213 abcd	1.16	20,855	0.98	s
5	2,408 ab	1.16	34,760	0.98	s
6	2,052 cde	1.12	123,809	0.91	s
7	2,198 abcd	1.09	24,629	0.98	s
8	1,898 ef	0.95	122,994	0.89	s
9	2,283 abc	1.02	69,758	0.94	s
10	1,810 efg	0.96	81,282	0.92	s
11	2,263 abc	1.18*	23,327	0.98	
12	1,575 g	0.72**	38,648	0.98	
13	1,847 efg	0.90	41,127	0.95	s
14	1,932 def	0.88	18,463	0.98	s
15	2,024 cde	0.93	97,757	0.90	s
16	1,774 efg	0.93	21,626	0.98	s
17	2,194 bcd	0.98	50,000	0.95	s
18	1,728 fg	0.93	102,004	0.90	s
Mean	2,075				

Means followed by the same letter are not significantly different at the 0.05 level.

†* and ** indicate significant difference from 1.00 at the 0.05 and 0.01 levels, respectively.

††* and ** indicate significant difference from 0 at the 0.05 and 0.01 levels, respectively.

s = Stable. A stable hybrid is the one with b not significantly different from 1.00 and mean square deviations (MSD) not significantly different from 0.

different from 0 (Table 16). Hybrids 1, 3, 4, 5, 7, 9, and 17 yielded higher than the average yield of 2,075 kg/ha over all hybrids. They were the desirable hybrids for grain yie.Ld. Hybrid 3 which had the highest yield (2,489 kg/ha) was the most desirable.

Figure 1 shows the response of three stable hybrids (5, 7, 14) to environmental indices. Hybrid 5 (b = 1.16) produced better in more favorable environments, and its performance was consistent. Hybrid 14 with b = 0.88 was expected to perform better in unfavorable environments.

Based on the R^2 (coefficient of determination) which measures the magnitude of the non-linear response and similar to the deviation mean square, only hybrid 2 was unstable (R^2 = 0.83).

The average regression coefficient and deviation mean square for each male are given in Table 17. All males were stable. Figure 2 shows the linear response of the three males to environments. Male 1 performed better in high yielding environments, and male 3 was expected to do relatively well in low yielding environments. Male 1 which yielded on the average higher than the average yield of all males was considered as desirable.

On the other hand, the regression coefficients and deviation mean squares of each female (Table 18) showed that all females were stable. Figure 3 shows the average response of three females to varying environments. Female 5 is expected ta do better in favorable environment conditions, while female 6 is expected to equal or exceed the average performance only in unfavorable conditions (b = 0.93 and mean = 1,785 kg/ha).

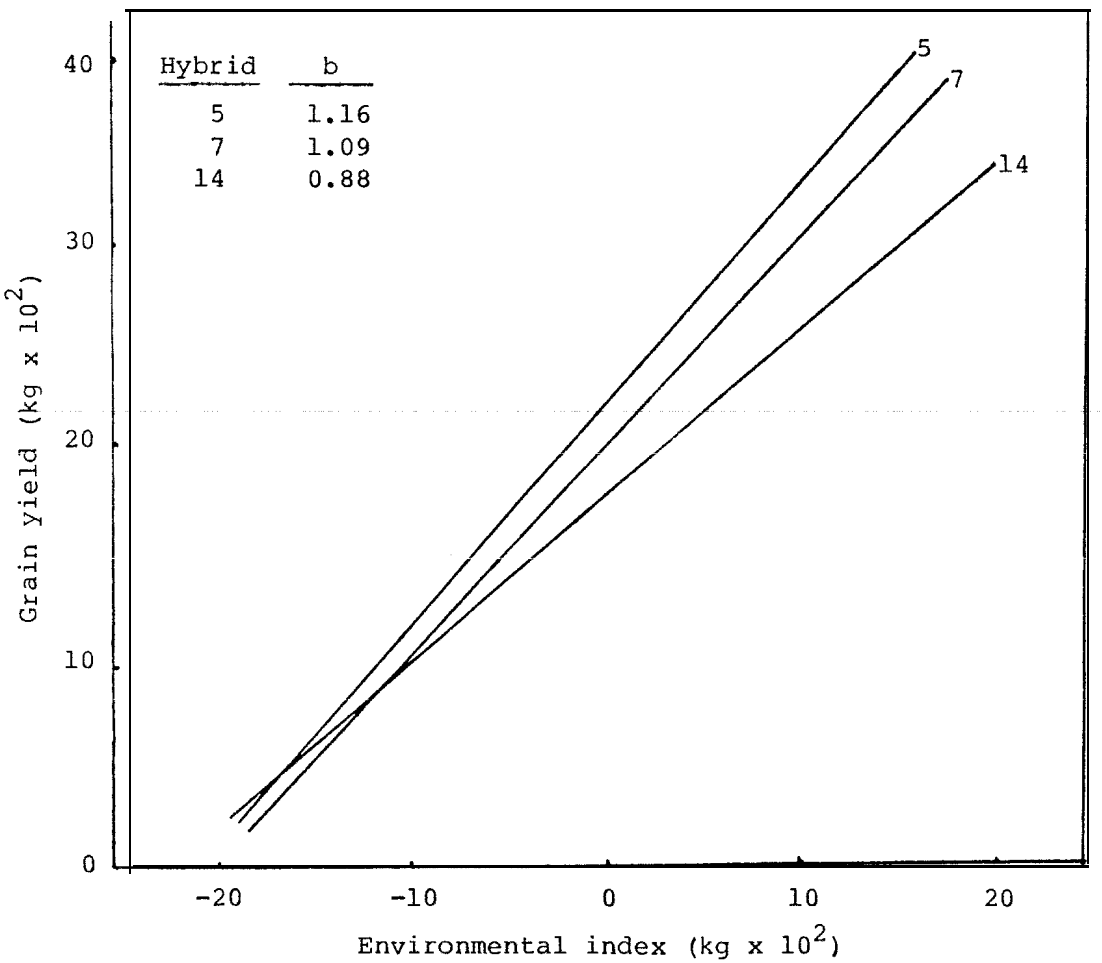

Figure 1. Regression of yield on environmental indices for three stable hybrids.

Table 17. Average stability parameters for grain yield of the three males.

Male	Mean	$\bar{b}$	MSD
1	2,305 a	1.09	89,310 s
2	2,004 b	0.99	60,107 s
3	1,917 b	0.92	55,829 s

Means followed by the same letters are not significantly different at the 0.05 level.

s = Stable. A stable genotype is the one with b (regression coefficient) not significantly different from 1.00 and mean square deviations (MSD) not significantly different from 0.

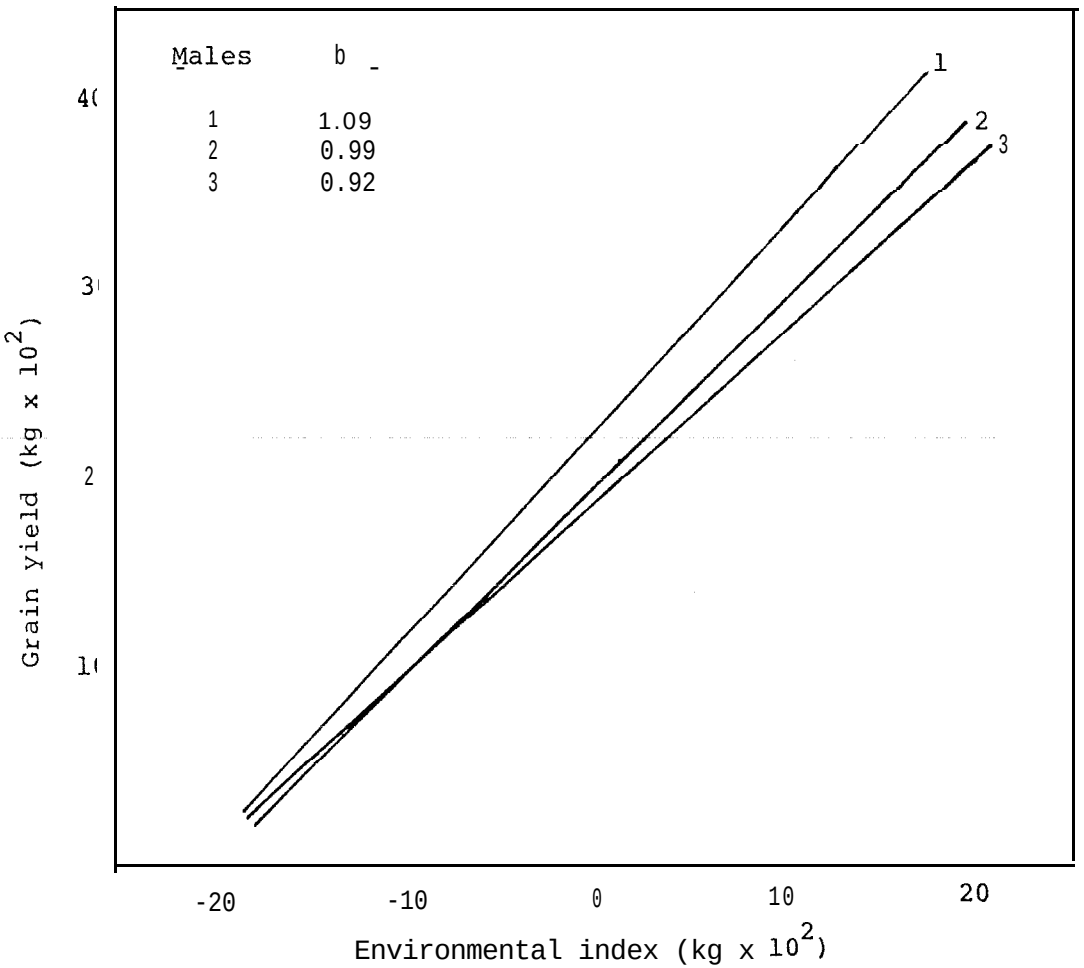

Figure 2. Regression of yield on environmental indices for the three males.

Table 18. Average stability parameters for grain yield for the six females.

Female	Mean	$\bar{b}$	MSD
	(kg/ha)		
1	2,076 bc	1.00	51,325 s
2	2,104 b	0.94	120,533 s
3	2,266 a	1.00	71,855 s
4	1,932 c	1.01	41,255 s
5	2,288 a	1.10	36,029 s
6	1,785 d	0.93	89,487 s

Means followed by the same letters are not significantly different at the 0.05 level.

s = Stable. A stable genotype is one with b (regression coefficient) not significantly different from 1.00 and mean square deviations (MSD) not significantly different f'rom 0.

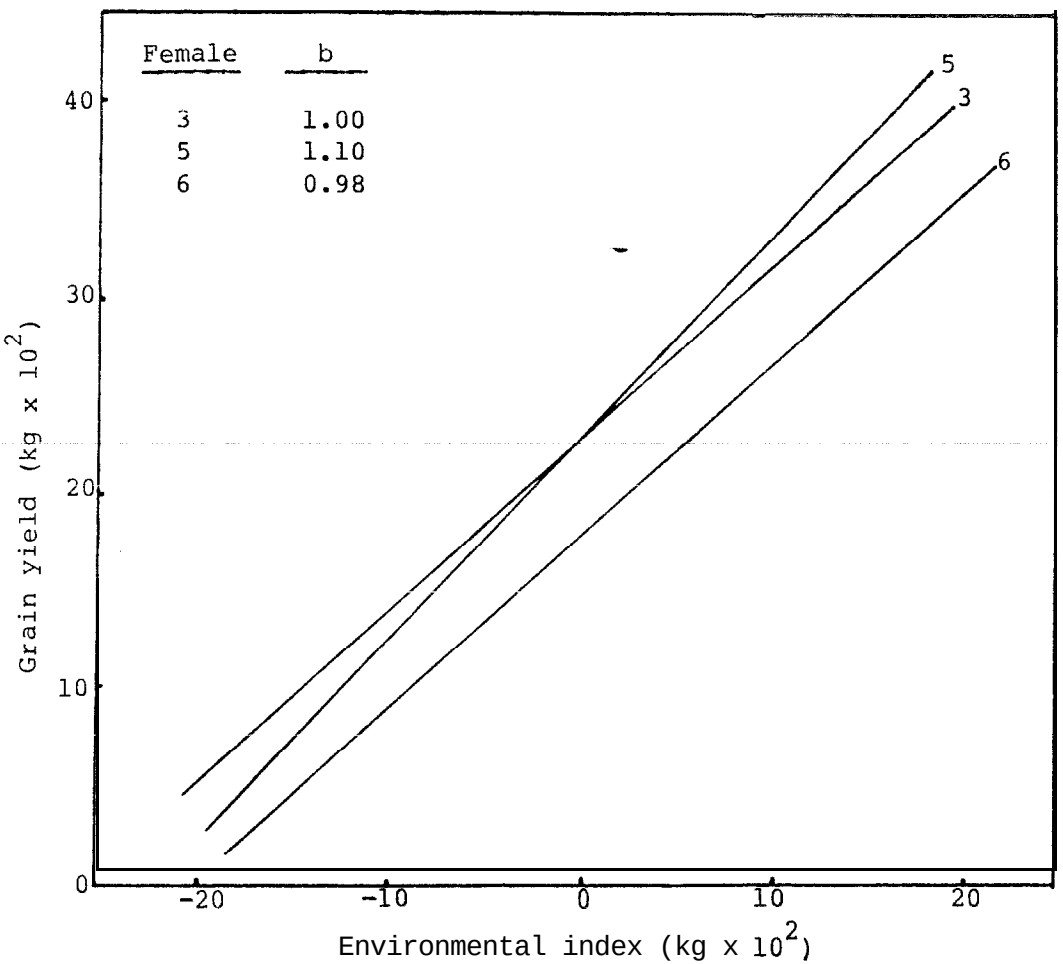

Figure 3. Regression of yield on environmental indices for three females.

Relationship Between Mean Yield Performance and Stability Parameters

The correlation between hybrid means and stability parameters (b, S_d^2) was determined. Mean yield was significantly and positively correlated with the regression coefficient for yield ($r = 0.73$). Therefore, the genotypes used tended to have high yields along with large regression coefficient.

On the other hand, there was a low correlation bet.ween mean yield and S_d^2 ($r = 0.15$). Since the association between mean yield and S_d^2 for yield was not significant, the two traits could be selected independently, i.e., selection of high yielding genotypes with low mean square deviations.

Relationship Between Stability Parameters and Coefficient of Determination (R^2)

The correlation between regression coefficients and coefficient of determination was not significant ($r = 0.30$). The correlation between R^2 and S_d^2 was significant ($r = -0.95$) . When stability of genotype is assumed to measure how well the actual yields of the genotypes are predicted, the result suggested that R^2 should be a satisfactory parameter for measuring stability. However, it does not give any information about the responsiveness of the genotype as shown by the low correlation with b.

Relationship Between Stability for Yield and Stability for Yield Components

Correlation coefficients among the stability parameters for grain yield and stability parameters for yield components are given in Table

19. A significant correlation was found between mean grain yield and mean 100-seed weight ($r = 0.83$) and mean seeds/m^2 ($r = 0.54$). This indicates that yield was dependent on seed weight and seeds/m^2. There was also a significant correlation between the regression coefficient of grain yield and the mean seed weight and seeds/m^2. A significant and negative correlation was found between b for yield and S_d^2 for plant height indicating that low mean square deviations for plant height enhances the response of millet to high yielding environments. There was also a significant positive correlation between S_d^2 for grain yield and S_d^2 for seeds/m^2 indicating that the stability for seeds/m^2 was related to the stability of grain yield. Correlations between grain yield stability parameters and those of days to 50% bloom were negative but were not significant. Thus, grain yield seems to increase when number of days to 50% decreases.

The results suggested that stability of grain millet yield was mostly rekated to the stability of seeds/m^2, while the overall yield production depends mostly on mean seed weight.

Table 19. Correlation coefficients between yield and the other traits for means and stability parameters.

	Grain yield parameters		
	Mean	b	S_d^2
Days to 50% bloom			
Mean	-0.34	-0.45	0.06
b	0.23	0.22	-0.27
S_d^2	-0.36	-0.43	-0.11
Plant height			
Mean	-0.09	-0.03	0.19
b	-0.37	-0.37	0.39
S_d^2	-0.20	-0.50*	0.17
100-seed weight			
Mean	0.83**	0.53"	0.05
b	0.40	0.19	0.22
S_d^2	0.25	0.31	-0.12
Seeds/m^2			
Mean	0.57**	0.54**	0.15
b	-0.11	0.41	-0.20
S^2	0.20	-0.17	0.73**

* and ** indicate significance at the 0.05 and 0.01 levels, respectively.

DISCUSSIO:N

Genotype x Environment Interaction

The yield trials were conducted at four locations in 1983 to evaluate the genotype x environment interactions for 18 millet hybrids. At each location, two experiments were planted. This gives eight environments. The analysis of the individual experiments showed that the individual error variances were not homogeneous, but the pooled error mean square from individual experiments appears to be the best estimate of error variance for the combined analysis whether the individual error variance are homogeneous or not. According to Cochran and Cox (1957), the heterogeneity of variances lead to too many significant results. Therefore, the relative magnitudes of the interaction components of variance are more important than their significance. The estimates of the interaction components of variance, hybrid x environment within location ($\hat{\sigma}^2_{HE/L}$), and hybrid x location ($\hat{\sigma}^2_{HL}$) were obtained from the combined analysis.

The relatively large $\hat{\sigma}^2_{HE/L}$ for 100-seed weight indicates that the relative performance of the hybrids across environments within a location was more inconsistent than across location for the trait. The $\hat{\sigma}^2_{HL}$ was higher than $\hat{\sigma}^2_{HE/L}$ for days to 50% bloom, plant height, grain yield, and seeds/m^2 suggesting that the performance of the hybrids was more inconsistent across locations. Thus, to reduce the magnitude of the interaction for the traits, the testing area should be divided into subregions.

From the results, it appears that millet responds differently to environments, and the hybrid x environment within a location interaction was more important for 100-seed weight, but for grain yield, plant height, days to 50% bloom, and seeds/m^2, the hybrid x location interaction was more important.

Grain Yield and Components Stability

It is commonly observed that the relative performance of different genotypes varies in different environments, i.e., there is a genotype x environment interaction which has been a challenge to fully understand the control of variability. The genetic variability is inferred from the phenotype. Therefore, screening for high yielding and stable genotypes becomes an important part of the plant breeding program.

The study was based on 18 hybrids grown in different environmental conditions. The Eberhart and Russell (1966) method was used for the stability analysis by estimating the linear regression (b) and the mean square deviations from regression (Sd). Linear regression (b) shows the response of a genotype to varying environments, while S_d^2 measures the dispersion around the regression line, i.e., how well the predicted response agrees with the observed. Eberhart and Russell (1966) considered S_d^2 to be the best measure of stability. A genotype with b value not significantly different from 1.00 and mean square deviations from regression not significantly different from 0 or as small as possible was considered as stable. A stable genotype will be more desirable when it has a mean yield greater than the average yield of all genotypes.

The hybrid x environment mean square was siynificant for all traits except for grain yield indicating that the performance of the hybrid varies with environment. There was no hybrid x environment interaction for grain yield. The lack of interaction for grain yield was expressed by the large number of stable hybrids. Fifteen out of 18 hybrids were stable. Seven hybrids were desirable. The absence of interaction might be related to the fact that the environments did not represent an extremely wide diversity in environmental conditions. For the other traits, although there was a sizable hybrid x environment interaction, more than half of the hybrids were stable. This indicates that more testing is required in order to have precise information on the stability of the hybrids for plant height, days to 50% bloom, 100-seed weight, and seeds/m^2.

The average regression coefficient and mean square deviations from regression for yield of the males and the females indicate that all parents were stable. This suggests that almost all parents could be used as parents in crosses for yield stability.

The significance of the correlation between mean yield and the regression coefficient for yield indicates that it is possible to have high yielding hybrids in favorable conditions. The yield of millet genotypes increases when environmental conditions improve. Similar results were reported by Eagles et al. (1977) in oats and by Busch et al. (1976) in wheat. The two traits are dependent, and selection for high response to environments will enhance grain yield.

The coefficient of determination (R^2) for yield was negatively and significantly correlated with the mean square deviation from regression (S^2_d) indicating that R^2 could be used for assessing the predicta-

bility of yield. High R^2 will indicate low nonlinear response. The contribution of various plant traits to yield stability is of interest to plant breeders. The finding of traits associated with yield allows the selection for yield stability through these traits. The mean square deviations from regression for seeds/m^2 was significantly correlated to the mean square deviations of yield. Selection of hybrid with low mean square deviations for seeds/m^2 appears to improve the stability of yield. Mean 100-seed weight and mean seeds/m^2 were positively and significantly correlated to mean yield. It suggests that both 100-seed weight and seeds/m^2 determine the yielding potential of the millet hybrids. On the other hand, high responsive hybrids in favorable conditions produce heavier seeds, ($r = 0.53$) and more seeds/m^2 ($r = 0.54$). Egharevba et al. (P983) found no significant correlation between weight of seeds and yield in millet. The existence of interaction may have caused the high correlation found in this study. The association between deviation mean square for plant height and regression coefficient for grain yield is not readily interpretable without knowledge about the relationship between plant height and yield. According ta Egharevba et al. (1983), there was a positive correlation between the two characters, but they concluded that there was no evidence that taller plants were more efficient than shorter plants in grain production.

Since the development of yield components is a series of sequential events, stress due to environmental factors at any stage might affect the final yield. Therefore, compensation for reduction of one component with an increase in another may be important for yield stability.

SUMMARY

The stability of 18 millet hybrids was studied in eight environments across Nebraska and Kansas using the Eberhart and Russell (1966) method. The objectives of the study were (1) to investigate the importance of genotype x environment interaction in a millet testing program; (2) to estimate stability parameters for each hybrid and identify stable hybrids for days to 50% bloom, plant height, 100-seed weight, seeds/m^2, and yield.

The relative magnitude of the components of variance due to hybrid x environment within location and hybrid x location indicated that interaction of hybrids with location was more important for grain yield, days to 50% bloom, plant height, and seeds/m^2. The relative magnitude of the components of variance showed that interaction of hybrid with environments within a location dominated for 100-seed weight. The reaction of the hybrids to location ox environment within location changes depending on the measured traits, i.e., on the sensitivity of the traits to change in conditions across locations or across environments with a location.

The hybrid x environment interaction was not significant for grain yield. Thus, more than 2/3 of the hybrids were stable for grain yield. Testing in a wider range of environmental conditions is needed before concluding about the general adaptation of the hybrids.

Grain yield was associated with seed weight and seeds/m^2. However, it was correlated higher with seed veight than to seeds/m^2. The statility of the hybrids for grain yield across environments was related

to the stability in seeds/m^2. Thus, selection for stability of grain yield can be done through seeds/m^2.

The full assessment of yield components to find those mostly related to stability of yield requires a broad investigation on all traits affecting yield over environments.

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