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Genotype x environment interaction, yield stability and adaptation responses of 25 single-cross maize (*Zea mays* L.) hybrids grown in Michigan

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GENOTYPE X ENVIRONMENT INTERACTION, YIELD STABILITY AND ADAPTATION RESPONSES OF 25 SINGLE-CROSS MAIZE (*Zea mays* L.) HYBRIDS GROWN IN MICHIGAN

By

Kingstone Mashingaidze

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ABSTRACT

GENOTYPE X ENVIRONMENT INTERACTION, YIELD STABILITY AND ADAPTATION RESPONSES OF 25 SINGLE-CROSS MAIZE (*Zea mays* L.) HYBRIDS GROWN IN MICHIGAN

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Genotype-environment interaction is of significant importance in plant breeding. Farmers are interested in varieties that perform consistently from year-to-year, while breeders prefer widely adapted varieties. Thus, ideally, a variety should be high yielding, widely adapted and stable. Various methods have been proposed for estimating variety adaptation and stability of field crops but none of them seem to be used as routine selection tools.

Twenty-five maize hybrids were evaluated in yield trials at eight locations over two seasons in Michigan. The yield trial data were used to : (1) examine the potential usefulness of adaptation and stability analyses in increasing the efficiency of selection and in making variety recommendations, (2) determine the associations among grain yielding ability, adaptation and stability parameter estimates, and (3) to compare different stability parameter estimates.

A major proportion of the significant GE interaction was made up of genotype x location interaction emphasizing the need to replicate more over locations than years. The linear regression coefficient (b value) was used as a measure of adaptation. Similar results were obtained from the use of a dependent and independent measure of the environmental index. The b values in conjunction with mean yields across environments enabled the identification of hybrids adapted to specific types of environments. High yielding widely adapted hybrids were obtained indicating that selection for wide adaptation does not necessarily mean selecting for mediocrity. Mean square deviations from regression, stability variance and coefficient of determination were used as measures of relative stability. These parameter estimates were highly correlated. Grain yielding ability, adaptation response (b value) and stability parameter estimates were not correlated suggesting that yield potential, adaptation and stability are independent traits which should be selected for independently and that it should be possible to develop varieties with various combinations of these traits. All the hybrids used in this study had highly significant deviation mean square and stability variance values suggesting that none of them were stable. Hybrids which had b values close to unity and/or were highly correlated with the others had relatively lower deviation mean square and stability variance values.

In memory of my grandfather, VaTitos MASHINGAIDZE

To my parents and relatives in Zimbabwe

To my wife, SIPIWE, my daughter,
RUMBIDZAI, and my son, RUVIMBO

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throughout the period of this study, and to my parents and relatives in Zimbabwe for their moral and spiritual support.

This dissertation is dedicated to my grandfather (VaTitos Mashingaidze) who passed away on May 25th, 1987.

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1. INTRODUCTION

In crop breeding programmes, many potential varieties are usually evaluated over a number of environments (locations and years) before the selection and release of desirable varieties. For quantitative traits (such as yield) the relative performance of different varieties often varies from one environment to another. The changes in the relative rankings of varieties and in the magnitudes of differences among them is defined statistically as the genotype-environment (GE) interaction. This phenomenon is caused by varietal differences in physiological reactions to different environmental conditions.

There is a general agreement among plant breeders that GE interactions occur with sufficient frequency and magnitude to be of notable importance in the development and evaluation of improved varieties. One important effect of GE interactions is to reduce the correlation between phenotype and genotype with the result that valid inferences become more complicated and progress from selection is reduced.

The changes in rank, which occur when varieties are evaluated over a range of environments, make it difficult for the plant breeder to decide which varieties should be selected. Often a variety's performance may be outstanding at one or more locations in one or more years, but be variable, mediocre or even substandard at other locations. Mean performance (e.g. yield) over all environments becomes inadequate as a basis for selection because it does not fully indicate consistency of performance.

Farmers are interested in high yielding varieties that give stable yields at a particular location from year to year. Breeders prefer to develop widely adapted and stable varieties. In making decisions on which varieties to select there are at least three questions to be considered:-

(i) How did the variety's overall performance (e.g. for yield) compare to the overall average performance of all the other (or one or more standard) varieties?

(ii) Is it better adapted to one type of environment than to another?

(iii) Was its mean performance consistent relative to the performance of all the other (or one or more standard) varieties?

That is, a breeder will want to ascertain how the variety compared with other varieties or standard varieties in performance level, adaptation and stability, respectively. Ideally a variety should be adapted to a wide range of environments, stable and above average in yielding ability. Performance tests over a series of environments when analyzed by the conventional combined analysis of variance give information on the magnitude of GE interaction but no assessment of stability and adaptation responses of individual entries. Complete answers to the above questions can be obtained from the use of statistical techniques that enable the assessment of stability and adaptation responses of the varieties from the performance data.

Regression techniques are useful in characterizing genotypes as to their range of adaptation and in identifying stable varieties or unusual performance at specific locations. When GE interactions are present, utilization of the adaptation and stability indexes could enhance the effectiveness of variety comparisons in making selections and variety recommendations. However, despite all the work that has been done on stability analyses in maize (Zea mays L.)and other field crops, regression techniques do not seem to be used as routine selection tools when genotypes have been evaluated in yield trials over a wide range of environments. In maize, the regression technique has been used to study the yield stability and adaptation of distinct types of maize hybrids, such as prolific vs non-prolific hybrids (Russell and Eberhart, 1968), single-cross vs double-cross maize hybrids (Eberhart, 1969), hybrids developed from improved vs unimproved germplasm (Fakorede and Mock, 1978), hybrids produced from selected vs unselected inbred lines (eGama and Hallauer, 1980), and in making comparisons of different methods used for determining stability (Prasad and

Singh, 1980). In the M.S.U. maize breeding programme potential hybrids are usually grown over a wide range of environments and, in the presence of GE interactions, stability analyses might provide useful additional information that will facilitate the selection process.

The present study was conducted :

(1) To examine the potential usefulness of stability and adaptation analyses in increasing the efficiency of selection and in making varietal recommendations, when GE interaction is present, by determining the relative yield stability and adaptation responses of 25 commercial maize hybrids grown in Michigan, which were developed without direct selection for stability and adaptation,

(2) To determine the associations among grain yield, stability and adaptation parameter estimates, in order to find out whether it is necessary to select for stability and adaptation *per se*, and

(3) To compare different stability parameter estimates.

2. LITERATURE REVIEW

The existence of genotype-environment (GE) interactions has long been recognized, the earliest reference, which indeed precedes the analysis of variance, being that of Fischer and Mackenzie (1923). In considering the manurial responses of different potato (Solanum tuberosum L.) varieties, they concluded that a product formula provided a better fit to the yields of the varieties in the different manurial treatments than did an additive formula.

The nature and importance of GE interactions in plant breeding have been reviewed in detail by Allard and Bradshaw (1964). As Comstock and Moll (1963) put it: **"because genetic factors are inferred from observations on phenotype, because selection is based on phenotype and because there is a potential contribution of interaction effects to phenotype of all quantitative characters, GE interaction is in some way involved in most problems of quantitative genetics and many problems of plant breeding".**

There are two possible strategies for a plant breeder interested in developing varieties which show a low GE interaction. The first one is the subdivision of a heterogeneous area for which the varieties are being bred into smaller regions that a breeder feels can be covered economically in the breeding programme, such that each of them has a more homogeneous environment and its own characteristic varieties (Eberhart and Russell, 1966; Francis and Kannenberg, 1978; Horner and Frey, 1957). The second one is the development of varieties which show a high degree of stability in performance over a wide range of environmental conditions (Eberhart and Russell, 1966; Francis and Kannenberg, 1978).

Stratification of environments is usually based on such predictable environmental variations as temperature gradients, length of the growing season, soil types, etc., (Allard and Bradshaw, 1964). Horner and Frey (1957) divided oat (*Avena sativa* L.) testing areas of Iowa into sub-areas within which the genotype-location interaction component of variance was substantially reduced. Abou-El-Fittouh, Rawlings and Miller (1969) used cluster analysis to define homogeneous regions of cotton (*Gossypium hirsutum* L.) variety trials in the US Cotton Belt. However, even with this stratification, the interaction of varieties with locations within a subregion, and with environments encountered at the same location in different years, (because of unpredictable environmental variations such as fluctuations in weather, e.g. amount and distribution of rainfall, temperature, etc.,) frequently remains too large (Eberhart and Russell, 1966).

Thus, it is important to develop widely adapted stable varieties that interact less with the environment in which they are grown. A variety must not only perform well in its area of initial selection but it also must maintain a high performance level in many environments within its intended area of adaptation (Weaver, Thurlow and Patterson, 1983). Extensive testing is required to identify varieties that have minimum interaction with environments, or possess greatest stability. Among those genetic materials in a set being tested, an ideal variety would be adapted to a wide range of growing conditions in a given production area, with above average yield and below average variance across environments. This is a working definition of stability (Saeed and Francis, 1983). Yield stability is of particular importance under subsistence agriculture, where control of environmental factors that limit production is limited, resulting in considerable seasonal yield variations.

2.1. ASSESSMENT OF STABILITY AND ADAPTATION RESPONSES

A large body of literature has been devoted to analytical techniques designed to clarify GE interactions in variety trials replicated over locations and years. Excellent reviews of these techniques have been published by Freeman (1973), Gotoh and Chang (1979), Hill (1975), Lin, Binns and Lefkovitch (1986), Moll and Stuber (1974), and Westcott (1986). The types of analyses can be grouped into:-

(1) the estimation of variance components and coefficients of variation;

(2) linear regression analysis;

(3) estimation of the contribution of each variety to the overall GE interaction;

(4) multivariate analysis; and

(5) other minor methods.

2.1.1. The estimation of variance components and coefficients of variation

2.1.1.1. Components of variance

Genotype-environment studies which partition the analysis of variance sum of squares (into genotype, environments, and GE interaction sources of variation) have helped to elucidate the nature, magnitude and extent of GE interaction (Comstock and Moll, 1963). Sprague and Federer (1951) showed how variance components could be used to separate out the effects of genotypes, environments and their interaction by equating the observed mean squares in the analysis of variance to their expectations on the random model. They used variance components to compare the GE interactions of single-cross and double-cross maize hybrids. Smaller GE interactions were obtained from double-cross than from single-cross hybrids suggesting that double crosses were more stable than single-crosses. However, this does not provide information concerning individual genotypic stability.

2.1.1.2. Coefficient of variation (CV)

Francis and Kannenberg (1978) proposed a genotype-grouping technique which they used in studying yield stability of 15 short-season maize hybrids in Southern Ontario, Canada. Varieties were grouped on the basis of mean yield and consistency of performance across environments. The conventional coefficient of variation (CV) for each genotype was used as a stability measure. The mean yield of each genotype across environments is plotted against its coefficient of variation over environments. With the grand mean and mean coefficient of variation serving as the base lines on the x- and y-axis, respectively, varieties can be classified into four groups as shown in Fig 1 below.

Group I --- varieties with high (above average) mean yield and low (below average) coefficient of variation,

Group II --- varieties with high (above average) mean yield and high (above average) coefficient of variation,

Group III -- varieties with low (below average) mean yield and low (below average) coefficient of variation, and

Group IV --- varieties with low (below average) mean yield and high (above average) coefficient of variation.

This genotype-grouping technique has no predictive value. However, it offers a simple, descriptive method for

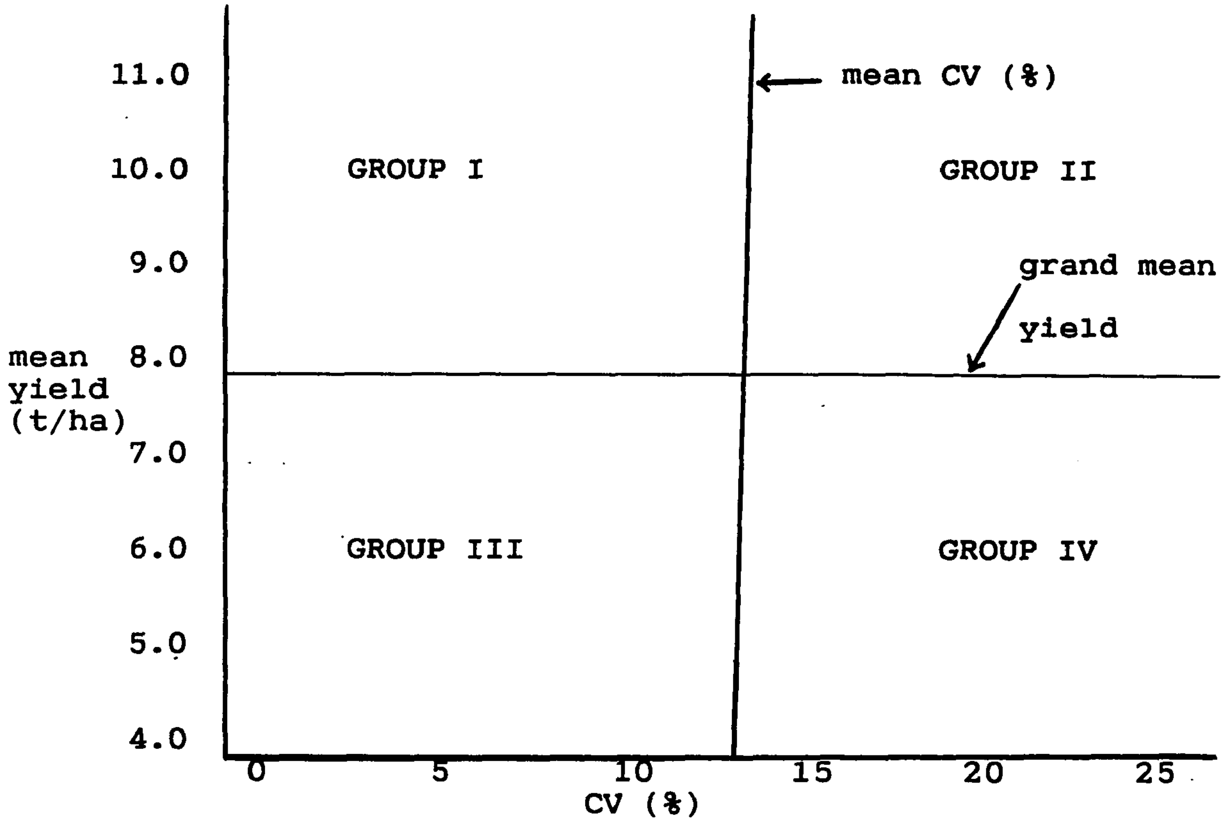


Fig 1. Mean yield plotted against coefficient of variation (adapted from Francis and Kannenberg, 1978)

grouping a large number of varieties from yield data collected over several environments. This is particularly useful during the initial screening stages of a breeding programme, where, because of the large numbers of individuals involved, it would be more practical to characterize varieties on a group basis rather than individually (Funnah and Mak, 1980; Ntare and Aken'Ova, 1985).

Mean yield and variation tolerance limits are flexible. For the breeder practicing mass variety screening, delimiting co-ordinates for mean yield and coefficient of variation can be conveniently set by check or standard varieties (Francis and Kannenberg, 1978). Lin et al (1986) showed that variance and coefficient of variation (CV) are equivalent.

2.1.2. Linear regression techniques

Although, in general, genetic effects are not independent of environmental effects, a number of authors (Baker, 1969; Breese, 1969; Eberhart and Russell, 1966; Finlay and Wilkinson, 1963; Perkins and Jinks, 1968; Yates and Cochran, 1938) observed that the relationship between the performance of different varieties in various environments and some measure of these environments is often linear or nearly so. From these observations, Freeman and Perkins (1971) concluded that there is strong evidence indicating a genuine underlying linear relationship between performance of specific genotypes and environmental conditions, even though this relationship does not always account for most of the interaction observed (Moll and Stuber, 1974). Because of this linear relationship, regression techniques have been used to characterize responses of genotypes in varying environmental conditions.

2.1.2.1. Phenotypic regression analyses

2.1.2.1.1. Yates and Cochran's (1938) regression technique

Yates and Cochran (1938) were the first to propose the linear regression technique for further examining the GE interaction term. In a study of barley (*Hordeum vulgare* L.) trials conducted over a number of environments, they recognized that the degree of association between varietal differences and general fertility (as indicated by the mean of all varieties) could be further investigated by calculating the regression of the yields of the separate varieties on the mean yields of all varieties. The object of taking the regression on the mean yield of all varieties rather than on the mean yield of the remaining varieties was to eliminate a spurious component of regression which would otherwise be introduced by experimental errors (Yates and Cochran, 1938).

The observed performance (Y_{ij}) of the i<u>th</u> variety ($i=1,2,...,v$) in the j<u>th</u> environment ($j=1,2,...,n$) can be expressed as:-

$$Y_{ij} = \mu + G_i + E_j + (GE)_{ij} + e_{ij} \qquad (1)$$

where, μ is the grand mean over all varieties and environments;

G_i is the additive genetic contribution of the i<u>th</u> variety, calculated as the departure from of the mean of the i<u>th</u> variety averaged over all environments ($\sum_i G_i = 0$);

E_j is the additive environmental contribution of the j<u>th</u> environment, calculated as the difference between and the mean of the j<u>th</u> environment over all varieties ($\sum_j E_j = 0$);

$(GE)_{ij}$ is the GE interaction of the i<u>th</u> variety in the $j\underline{th}$ environment $[\Sigma_i \Sigma_j (GE)_{ij} = 0]$; and

e_{ij} is the error attached to the $i\underline{th}$ variety in the $j\underline{th}$ environment.

To estimate the phenotypic regression coefficient (b) for a particular variety its performance (Y_{ij}) values are regressed onto the environmental means, that is $\mu + E_j$. Since is constant overall and G_i is by definition constant for a particular variety, this approach is in effect regressing $E_j + (GE)_{ij}$ as the dependent variate against E_j as the independent variate (Hill, 1975). If a linear relationship is established between these two variates then;

$$(GE)_{ij} = b_i E_j + s_{ij} \tag{2}$$

where b_i is the phenotypic regression coefficient of the $i\underline{th}$ variety ($\Sigma_i b_i = 0$); and s_{ij} is the deviation from the fitted regression line of the $i\underline{th}$ variety in the $j\underline{th}$ environment. The slope of the $i\underline{th}$ variety includes additive environmental variation besides that portion of the GE interaction variation which is a linear function of E_j (Hill, 1975). Substituting (2) in equation (1) gives:

$$Y_{ij} = \mu + G_i + (1 + b_i)E_j + s_{ij} + e_{ij} \tag{3}$$

Yates and Cochran (1938) showed that this regression accounted for a large part of the interaction in a set of barley trials. However, their ideas were not really taken up until Finlay and Wilkinson (1963) rediscovered the same technique, modified and used it for an analysis of adaptation in a trial of 277 varieties of barley grown in seven environments. Modifications of the regression technique have also been proposed by Eberhart and Russell (1966), Freeman and Perkins (1971), Hardwick and Wood (1972), Mather and Caligari (1974), and Perkins and Jinks (1968).

2.1.2.1.2. Finlay and Wilkinson's (1963) regression technique

Finlay and Wilkinson (1963) elaborated and extended the regression technique to describe the adaptability and stability of a variety using its linear regression coefficient. The mean yield of all varieties for each site and season is used as a quantitative measure of the environment. A relatively low mean yield of all varieties at a particular site and season indicates a low-yielding environment. A relatively high mean yield of all varieties indicates a high yielding environment. In this way the average yield of a large group of varieties is used to describe a complex natural environment without the complexities of defining or analyzing interacting edaphic and seasonal factors.

For a variety a linear regression of individual mean performance on the mean performance of all varieties in each environment is calculated. Because the individual variety mean performances are plotted against the mean performance of all varieties, the average response of all varieties has a regression coefficient of unity (b=1.0). Thus, the b values of varieties vary above and below 1.0. The responses of individual varieties can be assessed relative to this mean response.

Finlay and Wilkinson (1963) used the regression coefficient as a measure of both adaptation and stability. The varieties under test can be classified for stability into the following categories:-

(i) a regression coefficient not significantly different from unity (b=1.0) indicates average stability. The response of a variety is parallel to the mean response of all varieties in the trial;

(ii) a regression coefficient less than unity (b<1.0) indicates above average stability; and

(iii) a regression coefficient greater than unity (b>1.0) indicates below average stability. Small changes in the environment produce large changes in performance.

Absolute phenotypic stability would be expressed by a regression coefficient of zero (b=0). Performance in all environments would be the same. However, this would not be desirable because it is associated with low performance and the variety cannot make use of better production environments.

The mean yields of the varieties over all environments together with the regression coefficients determine the adaptation of the varieties, as illustrated in Fig 2 below. Varieties with average phenotypic stability (b=1.0) when accompanied by high mean yield performance over all environments are considered to have good general (wide) adaptability. On the other hand, if they show low mean performance they are classified as having poor adaptability. Varieties with above average phenotypic stability (b<1.0) are relatively less sensitive to environmental changes, and do not show large changes to their average performance. Such varieties are relatively more productive in low-productivity environments but, being insensitive to environmental changes, give low performance in more favourable environments. These are considered to be specifically adapted to low-productivity environments. Varieties with below average phenotypic stability (b>1.0) exhibit the opposite type of adaptation. Varieties in this category are highly sensitive to environmental changes. Performance (e.g. yield) changes at a rate well above the average of the group and under the most favourable growing conditions such varieties give the highest performance and can, therefore, be described as being specifically adapted to high-productivity environments.

Finlay and Wilkinson's (1963) concept of an ideal, widely adapted, variety was one with maximum yield potential in the most favourable environment, and maximum phenotypic stability (b=0). Their barley data showed that the varieties

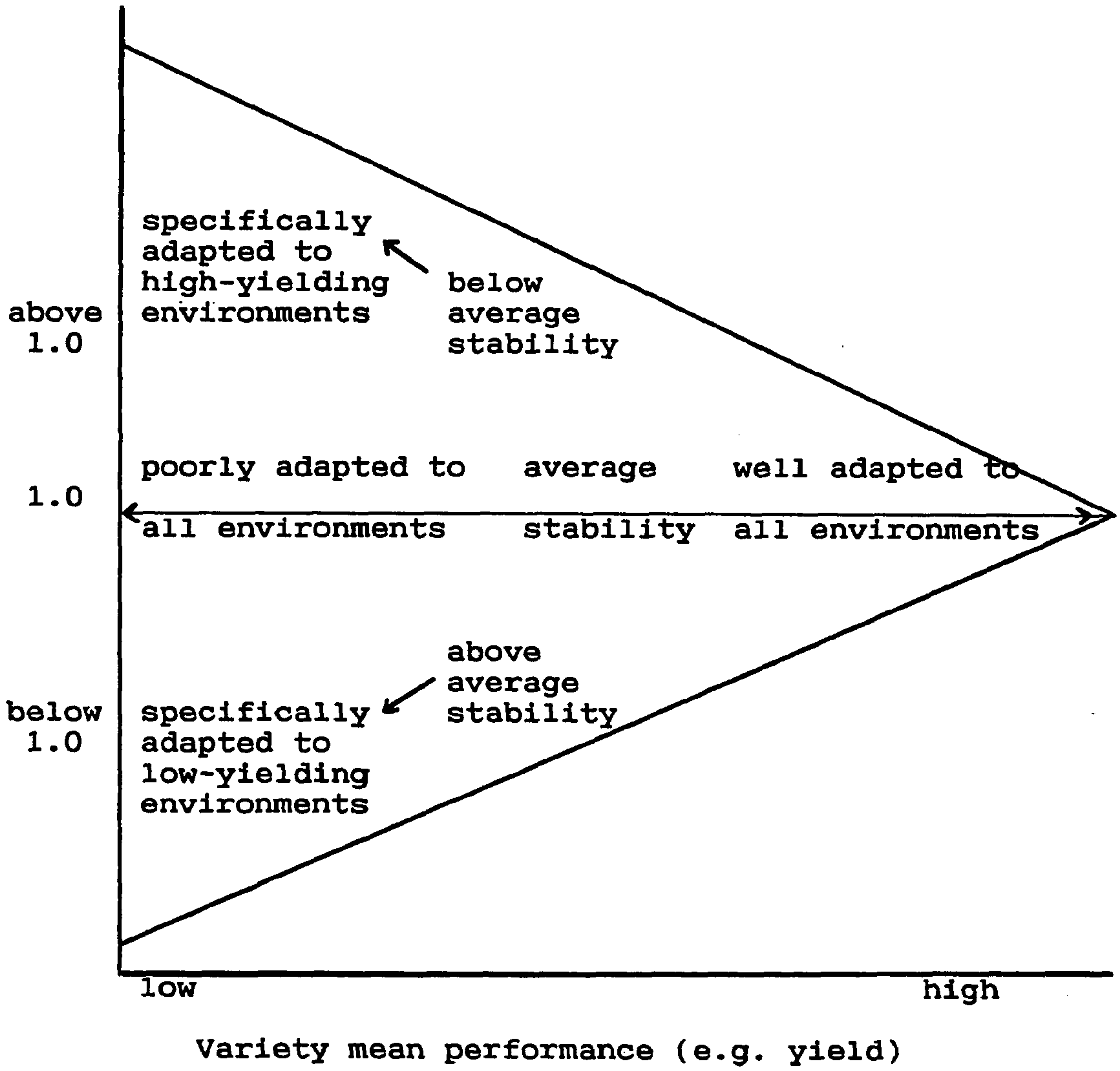


Fig 2. A generalized interpretation of varietal adaptation (adapted from Finlay and Wilkinson, 1963)

with high phenotypic stability (b<1.0) all had low mean yields and were unable to exploit highly favourable environments. They concluded that the breeder must compromise between yield potential and phenotypic stability in his/her search for an ideal variety.

Jowett (1972) disagreed with the contention of Finlay and Wilkinson (1963) that the lowest value for the regression parameter (b=0) is the most desirable. A regression coefficient of unity (b=1.0) would be the most desirable, because it indicates that the variety increases its productivity by an average amount as conditions improve. Smaller values imply failure to take advantage of better conditions, while larger values imply serious yield decline as conditions worsen.

Keim and Kronstad (1979) suggested that when dealing with adaptation to drought stress, grain yield in the most severely stressed environment takes on major importance. In conjunction with drought resistance, an average or better response to more favourable moisture conditions would be indicative of wide adaptation. They, therefore, proposed an ideal variety as one having both the highest yield under the most severely stressed environment expected and a strong response (b>1.0) to more favourable environments.

Finlay and Wilkinson (1963) used a logarithmic ($\log_{10}$) scale which induced a reasonable degree of homogeneity in experimental errors and also a high degree of linearity in the regressions. They noted that mean yields on a logarithmic scale correspond to geometric means on the natural scale. Jowett (1972) reported that if there are wide differences in the yielding abilities of entries low yielding varieties will be constrained by the additive nature of the model (model 1) to make a relatively small contribution to the interaction sums of squares, and hence have low values of regression coefficients, if the analysis is on the arithmetic scale, but not if the analysis is on the logarithmic scale.

Knight (1970) cautioned on the use of transformations. The effect of logarithmic transformation is to minimize the genotypic differences at the high performance values and maximize differences at the low performance levels. Thus, a plant breeder discriminating between varieties on the basis of regression values calculated on a logarithmic scale may be laying stress on differences at low yields for his/her selections (Knight, 1970). Breese and Hill (1973) compared the original and logarithmic scale in the analysis of regression and recognized that Log_{10} transformation resulted in more homogeneous error variances among varieties but introduced an abstraction which complicated both the visual interpretation of the graphs and the use of the estimated parameters in predicting response.

Several authors (Bilbro and Ray, 1976; Breese, 1969; Fakorede and Mock, 1978) prefer the use of the regression coefficient (b value) as a measure of adaptation rather than stability. Bilbro and Ray (1976) stressed that the regression coefficient is a measure of adaptation and that it should be of particular importance in areas where management, soil or climatic variables cause definable and distinct differences in yield levels. For example, in irrigated and dryland production areas the breeder will probably prefer to develop separate varieties for dryland and irrigated conditions. Thus, a breeder would be seeking varieties with $b>1.0$ for irrigated (high-yielding) conditions, and varieties with $b<1.0$ for dryland (low-yielding) conditions. In this sense b values would be used as an indicator of adaptation rather than stability (Bilbro and Ray, 1976).

2.1.2.1.3. Eberhart and Russell's (1966) regression technique

Eberhart and Russell (1966) modified the regression technique for evaluating stability by considering two empirical parameters; (i) the slope of the regression line (b), and (ii) the mean square deviation from the regression line (S_d^2). These parameters can be defined with the following model:

$$Y_{ij} = \mu_i + b_i I_j + s_{ij} \tag{4}$$

where, Y_{ij} is the mean of the ith variety at the jth environment ($i=1,2,...,v$; $j=1,2,...,n$);

μ_i is the mean of the ith variety over all environments;

b_i is the regression coefficient that measures the response of the ith variety to varying environments;

s_{ij} is the deviation from regression of the ith variety at the jth environment; and

I_j is the environmental index.

The environmental index is obtained as the mean of all varieties at the jth environment minus the grand mean, i.e.;

$$I_j = \Sigma_i Y_{ij}/v - \Sigma_i \Sigma_j Y_{ij}/vn ,$$

$$(\Sigma_j I_j = 0) .$$

The environmental index is merely a coded deviation of each environment from the grand mean over all environments (Eberhart, 1969) and this modification, from that of Yates and Cochran (1938), does not affect the value of the regression coefficient (Easton and Clements, 1973).

The appropriate analysis of variance is shown in Table 1 below:

Table 1. Skeleton stability analysis of variance (adapted from Eberhart and Russell, 1966)

Source of variation	d.f.
Total	nv-1
Varieties (G)	v-1
Environments (E)	n-1
GE interaction	(v-1)(n-1)
E (linear)	1
GE (linear)	v-1
Pooled deviations	v(n-2)
Variety 1	n-2
.	.
.	.
.	.
.	.
.	.
.	.
.	.
Variety v	n-2
Pooled error	n(r-1)(v-1)

The sums of squares for environments and GE interactions are added together and repartitioned into a linear component with one degree of freedom (1 d.f.), a linear component of the GE interaction with (v-1) degrees of freedom, and deviations from regression, the deviations being found separately for each of the v varieties with (n-2) degrees of freedom each. The trouble with this approach is that the sum of squares for the linear component between environments, which is allocated one degree of freedom, is the same as the total sum of squares for environments with (n-1) degrees of freedom (Perkins and Jinks, 1971; Freeman, 1973). Eberhart and Russell (1966) pointed out that in their approach the comparison of the linear component of the interaction against deviations from regression assumes that the deviations within the various varieties are homogeneous. The same is true in the Yates and Cochran (1938) approach. For this reason it is better to test the significance of the b values for a particular variety by comparing the appropriate sum of squares against the deviations from the regression for that variety rather than against the pooled deviation term (Freeman, 1973).

The first stability parameter (linear regression coefficient, b) is estimated by regressing the variety's mean yields in the respective environments upon the environmental indices. Thus:-

$$b_i = \Sigma_j Y_{ij} I_j / {}_j I_j^2 \quad .$$

The performance of each variety can be predicted by using the estimates of the parameters, where;

$$Y_{ij} = X_i + b_i I_j \quad ,$$

and , X_i is an estimate of the μ_i. The deviations $\{s_{ij} = (Y_{ij} - Y_{ij})\}$ can be squared and summed to provide an estimate of the second parameter (S_d^2):-

$$S_{di}^2 = [\sum_j s_{ij}^2 / (n-2)] - \sigma_e^2 / r \quad ,$$

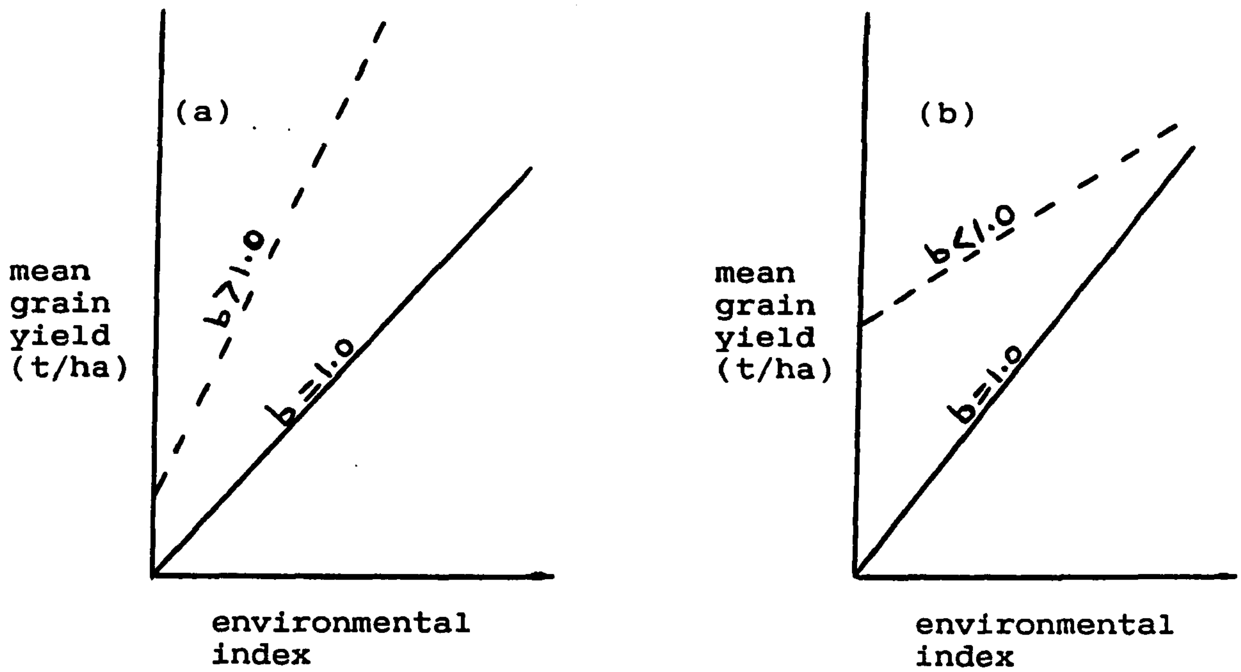
where, ${}_e^2/r$ is the estimate of the pooled error (or the variance of a variety mean at the j<u>th</u> location), and

$$\Sigma_j \, S_{ij}^2 = [\sum_j Y_{ij}^2 - Y_{i.}^2 / n] - (\sum_j Y_{ij} I_j)^2 / \sum_j I_j^2 \ .$$

This model provides a means of partitioning the GE interaction of each variety into two parts; (i) the variation due to the response of the variety to varying environmental indexes (sum of squares due to regression), and (ii) the unexplainable deviations from the regression on the environmental index.

Eberhart and Russell (1966) defined a stable variety as one with a regression coefficient of unity (b=1.0) and mean square deviation from regression equal to zero ($S_d^2 = 0$). This would be obtained if the variety responds exactly the same as the mean response of the population in each environment (to environmental changes) and does not interact with the environments (Marquez-Sanchez, 1973). All varieties with other combinations of values of b and S_d^2 (i.e. b=1.0 and $S_d^2 \neq 0$; or b$\neq$1.0 and $S_d^2 = 0$; or b$\neq$1.0 and $S_d^2 \neq 0$) would all be unstable.

In addition to these two parameters (b and S_d^2), a breeder usually wants a variety with a high mean performance (greater than the grand mean) over a wide range of environments. Thus, an ideal variety would be one with a high mean performance over a wide range of environments, average response to environments (b=1.0) and minimum deviations from regression ($S_d^2 = 0$). Eberhart (1969) reported other types of acceptable responses as shown in Figs 3a and 3b below. With a regression coefficient above unity (b>1.0) a variety can still give above average yields in all environments (Fig 3a).



Figs 3a and 3b. Acceptable responses to varying environments if the deviation mean square is non-significant (adapted from Eberhart, 1969)

This is also true if b<1.0; however, the mean yield must be well above average in such instances (Fig 3b). Gray (1982) reported that because yields of most perennial forage grass clones, e.g. orchardgrass (Dactylis glomerata L.) decline over years, clones with b values less than unity (b<1.0) would have less decline in yield over years. An ideal clone in this case would be one that has a regression coefficient less than unity (b<1.0), high yield and low deviation from regression.

Eberhart and Russell (1966) tested the application of their model to maize yield trial data. The GE(linear) sum of squares were not a very large proportion of the GE interaction. They concluded that S^2_d appeared to be a very important stability parameter. As large values of S^2_d were obtained for some lines and crosses, the data were fit to a quadratic model. The reduction in the deviation mean square was negligible, however, so that large deviations were not caused by a quadratic response. On the other hand, Schnell and Schmidt (1975) found quadratic regression to be more appropriate than linear regression in a study of yield and adaptation of medium-maturing maize hybrids.

Since Eberhart and Russell (1966) suggested the use of the deviation mean square (S^2_d) as a second stability parameter, great attention has been focused on it. Bilbro and Ray (1976), Breese (1969), Langer, Frey and Bailey (1979), and Perkins and Jinks (1968) strongly advocated its use as a stability parameter and it has received wide acceptance as evidenced by numerous publications using it.

When only a small portion of GE interaction is due to heterogeneity among regression coefficients, characterization of varieties by regression coefficients is not effective (Baker, 1969; Shukla, 1972). Under such conditions the deviation mean square provides additional information and may be the most appropriate parameter for evaluating varietal stability (Baker, 1969; Eberhart and Russell, 1969). Small, non-significant deviation mean square estimates (S^2_d) indicate linear responses to environments with no specific interactions, and hence variety response is highly predictable when based on site mean yield (Keim and Kronstad, 1979). Significant deviation mean squares indicate non-linear response or specific interactions with environments (eGama and Hallauer, 1980; Joppa, Lebsock and Busch, 1971).

Bilbro and Ray (1976), and Breese (1969) emphasized that the regression coefficient should be used as a measure of adaptation response rather than stability. Breese (1969) reported that the variability of any variety with respect to the environment can be subdivided into a predictable part and an unpredictable part corresponding to deviation mean square. Because the regression part can be predicted and to some extent controlled (by selecting specific genotypes for specific locations), it is not useful to consider this component of GE interaction as a measure of stability. Breese (1969) suggested that the term stability should be reserved to describe measurements of unpredictable irregularities in the response to environment as provided by the deviation from regression. However, it might be dangerous to place too much importance on the deviation from regression because it includes not only biological stability but also experimental error indespensable with biological data (Hill, 1975).

Edmeades (1984), Freeman (1973), Hardwick and Wood (1972), Lin et al (1986), and Shukla (1972) questioned the validity of the deviation mean square from regression as a stability parameter. Hardwick and Wood (1972) stated that in terms of the underlying model the deviations (s_{ij}) are not independent of the regression on the environmental index, so that S is not a meaningful stability parameter. Edmeades (1984) indicated that the regression analysis takes no account of curvilinear relationships between yield and the environmental index. Thus, stable varieties could be rejected because of deviations from linearity.

Lin et al (1986) argued that the regression model for GE interaction is a descriptive model based on the data being analyzed, and not a prediction model as Breese's (1969) argument seemed to assume. For a useful prediction model, the independent variable must be measurable prior to the experiment, and then the deviation mean square from regression may have a deterministic property that can be associated with varieties. However, for the descriptive linear regression model considered in the regression technique, the independent variable (environmental index) cannot be measured prior to the experiment. It is no more than a data based device to represent the environment so that the variety's response can be studied quantitatively. Because the model is purely empirical, the deviation mean square for it does not have a deterministic property such as may be the case for a prediction model. Essentially the deviation mean square of this model indicates no more than how good is the fit, but has no direct bearing on the variety's stability

(Lin et al.,1986). A poor fit (i.e. small r^2 or large S_d^2), or a heterogeneous deviation mean square should be taken as an indication that the use of the linear regression model to estimate stability is not adequate and that other approaches should be investigated (Lin et al., 1986).

Moll, Cockerham, Stuber and Williams (1978) noted that the regression is a function of both (i) the responsiveness of the varieties to the environment, and (ii) of the correlations of the responses of varieties in different environments. Caution is required when the correlations vary and are small. Entries whose responses are poorly correlated do not provide reliable environmental indexes for each other. The most similar varieties largely determine the values of the environmental means and understandably these varieties will show little deviation from the linear regression (small S_d^2). On the other hand, varieties that differ from the majority of varieties under consideration, either below or above their optimum, will show a marked deviation around the regression line and hence appear unstable (Knight, 1970). Thus, a variety with a specific desirable trait, such as disease or drought resistance, may deviate significantly from the regression at sites whose mean yield is depressed by these factors, and a desirable variety such as this may be discarded (Edmeades, 1984). Therefore, where deviations from regression are used to measure stability one must go more into the underlying biological basis for any differences in stability of response which might be present (Hill, 1975). Also, because of the relative nature of the regression technique, the deviation from regression is not a specific property of the variety. Since the mean yield of all varieties is used as a standard response in each environment, the relative ranking of an entry for stability varies according to the average response of the group of entries with which it is compared. A variety is stable only with respect to the other entries in the test with no assurance that it will appear stable if assessed with another set of varieties. For example, in a set of varieties (A,B,C,D,E), A may be assessed stable and B unstable if A resembles C,D,E more closely than does B. However, in the set of varieties (A,B,F,G,H), A may be considered unstable and B stable if A is less like F,G,H than is B. Easton and Clements (1973) found that by choosing a subset of varieties it was possible to make a previously stable variety appear unstable. They concluded that the degree of departure from linearity is not an adequate measure of instability and may be misleading if used as a measure of stability. Lin et al (1986) concluded that, until such time as the environmental index can be replaced by actual environmental factors, such as temperature or rainfall, etc., (leading to a prediction model), the use of mean square deviation from regression as a stability parameter is difficult to justify.

2.1.2.2. Genotypic stability parameters

2.1.2.2.1. Stability analysis by structural relationship

Tai (1971) outlined a method which can be regarded as a special form of that of Eberhart and Russell (1966). The GE interaction effect of the ith genotype is partitioned into two components (α_i and λ_i) based on the principle of structural relationship analysis. This is in order to overcome the limitations of regressing one set of variables onto another which is not independent of them (Hill, 1975). The parameter α_i measures the linear response of the ith variety to the environmental effects, and λ_i is the deviation from the linear response in terms of the magnitude of the error variance. If the variance component for deviations from linearity of the ith variety is S^2_{di} and the error variance is σ^2_e , then

$$\alpha_i = \frac{S^2_{di} + \sigma^2_e}{\sigma^2_e} .$$

The two components are defined as genotypic stability parameters and are related to the phenotypic stability statistics of Eberhart and Russell (1966) as follows (Tai, 1971,1979):-

$$\alpha_i = \frac{MSL}{MSL-MSE} (b_i - 1) , \text{ and}$$

$$\lambda_i = \frac{(v)(n-2)S^2_{di}}{(v-1)(n-1)\ MSE/r} - \frac{\alpha_i(b_i - 1)MSB}{(v-1)MSE}$$

where, b_i and S^2_{di} are the phenotypic stability parameters of Eberhart and Russell (1966);

MSL, MSB and MSE are the mean squares due to environments, replications within environments and error deviates, respectively;

v is the number of varieties, n is the number of environments, and r is the number of replications.

Tai (1971) showed that b_i -1 is a biased estimate of α_i, being always smaller in absolute value. In practice b_i-1 will be smaller than α_i except when b_i = 1. The difference between S^2_{di} and λ_i can be minimized by using similar numbers of varieties and environments in the experiment or when the sample of varieties and environments employed is large (Hill, 1975).

Tai (1971) gave the approximate procedures for testing $\alpha=0$ and $\lambda_i=0$. Tai (1971) distinguished between the linear component of interaction and the additive effects of the environments, so that the regression coefficients have a mean of zero, as do those of Perkins and Jinks (1968), rather than of 1.0 as do those of Eberhart and Russell (1966). Also, whereas Eberhart and Russell (1966) subtract a pooled error estimate from the non-linear component of the interaction so that a stable variety has a S_d^2 value of zero, Tai (1971) divides the non-linear interaction term by the pooled error estimate, so that the equivalent value of his parameter (λ) is 1.0. That is ;

$$S^2_{di} = [\sum_j s^2_{ij}/n-2] - \sigma^2_e/r \text{ , for Eberhart}$$

and Russell (1966), and

$$\lambda_i = \frac{S^2_{ij} + \sigma^2_e}{\sigma^2_e} \text{ , for Tai (1971),}$$

where, $\sum_j s^2_{ij}/n-2$ is the deviation from the regression mean square, and σ^2_e is an estimate of the pooled experimental error, a constant for all varieties in the experiment.

Like Finlay and Wilkinson (1963), Tai (1971) defined as perfectly stable a variety which does not respond at all to changes in the environment, that is, one with a regression coefficient of minus one (α_i = -1) and a low non-linear interaction component (λ_i = 1.0). Tai (1971) concluded that perfectly stable varieties probably do not exist and plant breeders will have to be satisfied with obtainable levels of stability. A variety with average stability would be one with α_i = 0 and λ_i =1.0.

2.1.2.2.2. Perkins and Jinks' (1968) regression technique

Perkins and Jinks (1968) proposed a method that is similar to that of Eberhart and Russell (1966) except that the observed values are adjusted for location effects before the regression. If there are v varieties and n environments, the GE interaction can be partitioned into two orthogonal terms, one measuring that portion of the GE interactions which is due to differences between the fitted regression lines (heterogeneity between regression lines) with (v-1) degrees of freedom and the other measuring the deviations of the observed values around these fitted regression lines with (v-1)(n-2) degrees of freedom. If significant GE interactions are present, either or both of these terms will be significant when tested against experimental error. This approach, commonly known as joint regression analysis, has been widely adopted in practice. The null hypothesis tested by the joint regression analysis is that no relationship exists between the GE interactions and the additive environmental component apart from that due to chance variation. Where the heterogeneity portion alone is significant it may be concluded that within each genotype the rate of change of the interaction does not vary with the environment. Each genotype has, therefore, its own characteristic linear response to environmental change. If, by contrast, only the residual portion is significant, either no relationship or no simple relationship exists between the genotype and the environments. More often than not, however, both items prove to be significant. When this occurs the heterogeneity portion should be re-tested against the residual portion to determine whether it accounts for a significant proportion of the GE interaction variance.

Perkins and Jinks (1968) employed biometrical genetics techniques to obtain a direct estimate of β. With reference to equation (1) i.e.,

$$Y_{ij} = \mu + G_i + E_j + (GE)_{ij} + e_{ij}, \qquad (1)$$

their method estimates the linear regression of $G_i + (GE)_{ij}$ on E_j for each genotype. Since G_i is a constant for a particular genotype, this is equivalent to regressing $(GE)_{ij}$ on E_j (Hill, 1975). Substituting β in equation (1) gives;

$$Y_{ij} = \mu + G_i + E_j + (1 + \beta_i)E_j + s_{ij} + e_{ij}. \qquad (5)$$

The genotypic regression coefficient (β) of Perkins and Jinks (1968) and the phenotypic regression coefficient (b) of Eberhart and Russell (1966) are equivalent according to the relationship $b = \beta+1$. Thus, β is the deviation of b from unit regression.

The average response of all genotypes has a regression coefficient of zero ($\beta=0$) and the responses of individual genotypes can be assessed relative to this mean response. To determine if β is significantly different from zero for each genotype, the regression mean square is compared with the deviation mean square for that genotype. The significance of β can also be tested by testing the departure of $(1+\beta)$ from unity.

A β value of zero indicates a genotype that shows average sensitivity or average response to environments of varying levels of productivity. A significantly high positive value indicates a variety with greater than average sensitivity to environmental variation. A significantly high negative value indicates a variety relatively insensitive to increased environmental productivity. The ideal variety would have a high mean yield, a regression coefficient of zero and minimum deviations from regression. Although a positive regression coefficient would seem more desirable, this usually results in lower-than-average yields in unfavourable environments (Weaver, et al., 1983). A cultivar with a positive regression coefficient would be better adapted to high-yielding environments, but would lack the wide adaptation of the ideal genotype.

2.1.2.3. Limitations of the regression technique

Limitations of the regression technique have been discussed by Byth, Eisemann and Delacy (1976), Easton and Clements (1973), Freeman (1973), Freeman and Perkins (1971), Hill (1975), Knight (1970), Lin et al (1986), and Witcombe and Whittington (1971).

2.1.2.3.1. Statistical limitations

2.1.2.3.1.1. The environmental index is subject to error

Statistical objections have been raised to the regression technique. In common with many other biological associations which are measured by regression or correlation, the regression technique suffers from the drawback that the environmental index, composed of the mean value of genotypes, is subject to error (Hill, 1975). The environmental index represents only an estimate of the true environmental effect, and so its variance contains an error component presumed to be uncorrelated with the dependent variable. This phenomenon is called the attenuation effect, and results in biased estimates of the regression coefficient (Tai, 1971). However, when a large number of genotypes are included in the experiment and the environmental range is such that the among environments mean square is significantly greater than the error mean square, any bias which results should not prove serious in practice. While reducing differences among estimated coefficients, it cannot disturb their ranking (Hardwick and Wood, 1972).

2.1.2.3.1.2. Heterogeneity of error variances

The validity of the joint regression analysis of variance depends chiefly upon the assumption that the errors attached to the individual regression coefficients are homogeneous. Failure of this assumption not only raises questions relating to the stability response (Breese, 1969), but it also makes the analysis and interpretation of the results more difficult (Hill, 1975). The difficulties occur when comparisons are made between the errors attached to the individual genotypes, because the sum of squares for residual deviations, with (v-1)(n-2) degrees of freedom cannot be partitioned orthogonally amongst the v genotypes. To effect such a partition requires that the whole of the within-genotype variation, with v(n-1) degrees of freedom, is taken into account (see Eberhart and Russell, 1966). It must be remembered, however, that the within-genotypes sum of squares includes variation due to environmental sources besides that due to GE interactions. Since the attaching of errors to the fitted regression lines will account for v(n-2) degrees of freedom, which is larger than the degrees of freedom available for residual deviations, some bias in the estimates of these errors is to be expected, and they must, therefore, be treated with caution (Hill, 1975). Also, the estimates of the regression coefficients will have different precisions making comparisons among the regression coefficients tedious.

2.1.2.3.1.3. Non-independent environmental indexes

A basic objection to many of the regression analyses is the choice of measurement of environmental effects on which the regression is made. The mean performance of all varieties grown in a specific environment is usually used to assess the environment. Thus, the variety means contribute to, and hence are not statistically independent of, the environmental means on which they are regressed. This does not provide an independent measure of environmental effects and, therefore, does not satisfy the requirements of a regression analysis. This results in biased estimates of the regression coefficient (Freeman, 1973; Freeman and Perkins, 1971; Shukla, 1972; Tai, 1971). Freeman and Perkins (1973) suggested that the whole regression approach should be based on the use of an independent measure of the environment, either biological or physical. It would be even better if environmental values could be measured without error.

Many ways have been suggested to provide an independent assessment of the environment. These are as follows:-

2.1.2.3.1.3.1. Independent biological measures of the environment

Independent biological methods of assessing the environment can be grouped into the following major categories;

2.1.2.3.1.3.1.1. The use of a genotype(s) closely related or similar to those under test to assess the environment

These may be inbred lines or parental genotypes (Bucio-Alanis and Hill, 1966; Freeman and Perkins, 1971; Hill, 1975;

Tan, Tan and Watson, 1979). An index based on the inbred parents will provide an independent measure of the environment for the F_1 and later, segregating generations (Bucio-Alanis, Perkins and Jinks, 1969). The environment assessment material should be closely related to the trial material as much as possible. In most practical situations where size of the experiment is often a limiting factor, the use of a few genotypes for assessing the environment would be preferable. A single appropriately chosen genotype can provide a satisfactory measure of the environment (Fripp, 1972).

2.1.2.3.1.3.1.2. The use of extra replications of the full set of genotypes to assess the environment

Perkins and Jinks (1973) recognized that the regression of members of one group of genotypes onto an index derived from another is likely to be biased by differential interaction of the two groups with the environment. Entries whose responses are poorly correlated do not provide reliable environmental indexes for each other. As an alternative, Perkins and Jinks (1973) used extra replicates of the full set of genotypes to assess the environment. This gives environmental values which correspond very closely to the average response of the trial genotypes. This modification has also been reported by Fripp (1972), Hill (1975), and Snoad and Arthur (1976). The use of extra replications, however, does not seem to be an efficient use of limited resources.

2.1.2.3.1.3.1.3. The use of an environmental index which explicitly excludes the genotype being regressed on it

An estimate of the regression coefficient of the ith genotype may be computed by regressing the performance of the ith genotype onto an index composed of the remaining genotypes (Mather and Caligari, 1974). This removes the statistical objection and part of the correlation which occurs when using a dependent environmental index (Mather and Caligari, 1974; Moll et al., 1978; Snoad and Arthur, 1976; Wright, 1976).

The advantage of this modification is that it does not require extra varieties or replicates in the experiment, though estimates so obtained will be distorted, both by error variation and by any departures from linearity on the part of the individual regressions (Hill, 1975).

2.1.2.3.1.3.1.4. The use of the mean of one or more standard (check) genotype(s) to assess the environment

Standards or checks (e.g. recommended commercial varieties) are usually included in variety trials as a reference point for comparisons of performance. The mean response of one or more standard varieties can be used to assess the environment (Bilbro and Ray, 1976; Fripp, 1972; Perkins and Jinks, 1973).

From a practical standpoint, breeders would want to compare their material against the best available varieties or those most widely produced in the area. If this is the case, the adaptation of the standards are secondary in importance because the breeder would be interested in how the other materials performed in comparison with the standards and not how the standards performed relative to each other (Bilbro and Ray, 1976).

The advantage of this approach is that the group of the standards can be updated as the breeding materials are improved. New varieties superior to the standards serve as standards for later cycles of testing. Thus, the standards would get successively better and the quality of the breeding materials would always be tested against an ever-improving set of standards. This should lead to the development of additional superior varieties (Bilbro and Ray, 1976).

The disadvantage of this approach is that some of the trial varieties may not respond in the same way as the standards used to assess the environment . The environment assessment material should be closely related to the trial varieties as much as possible. The linearity of response decreases as the varieties used to assess the environment become too distantly related to the test varieties (Fripp, 1972).

Although the use of these four methods provides the desired independence between environmental and genetic effects, they require the division of resources available, additional experimental costs, or the discarding of some data from the interaction analyses, and are inefficient with regard to minimizing sampling errors (Moll and Stuber, 1974; Perkins and Jinks, 1973).

Several authors (Bilbro and Ray, 1976; Fripp and Caten, 1971; Perkins and Jinks, 1973; Snoad and Arthur, 1976; Tan et al., 1979; Williams, 1975) reported that similar results were obtained from regression of a large number of genotypes on their environmental means and on values derived from other closely related sets of control genotypes, suggesting that the conclusions drawn from regression data were unaffectd by the choice of measure of the environment. Perkins and Jinks (1973) concluded that it was not important whether a dependent or independent measure of environmental values was used provided these were based on large numbers of observations. In fact, the increased size of the sampling variances resulting from the use of fewer experimental units for the independent environmental assessment would probably be more serious than the lack of independence resulting from the use of all the experimental material for the environmental assessments. Perkins and Jinks (1973) found that regressions on means derived from only a few independent genotypes were sometimes so insensitive as to give rise to problems of interpretation.

2.1.2.3.1.3.2. Independent physical measures of the environment

The environment can also be assessed by physical factors such as climatic measures (e.g. amount of rainfall, temperature, etc.,), soil fertility levels, etc. Regressions of yield on environmental variables have been calculated and those for individual varieties compared by various workers. Fripp (1972) compared both biological and physical measures of the environment and found that the analyses, for a large number of varieties, gave very similar results for all reasonable external measures and the environmental mean. Similar results were reported by Fakorede and Mock (1978).

In field situations many environmental factors influence growth and yield. Of these some such as temperature, rainfall (amount and distribution) , etc., cannot be controlled, and they fluctuate rapidly and the exact nature of the environmental variables is rarely known. Locations usually differ with respect to many environmental factors and measurement of any one physical factor will not adequately indicate the productivity of a location (Easton and Clements, 1973). Each environment represents an amalgam of several factors (nutrient levels, moisture levels, light, etc.,) each of which vary continuously and independently of the others. Faced with this problem, recourse has been made to a biological as opposed to a physical assessment of the environment (Hill, 1975). Thus, a suitable index of the productivity of an environment would be the mean performance of genotypes because it provides an estimate of the combined effects, on e.g. yield, of all the physical and biological components of the environment. This approach is valuable where an assessment is being made of many varieties but ultimately it will be necessary to determine the major limiting factors influencing yield (Knight, 1970).

Breese (1969) stressed that:"the phenotype is the product of the genotype and its environment. Therefore, it is just as apposite to numerically grade an environment by its mean expression over a range of genotypes as it is to measure a genotype by its mean expression over a range of environments. The fact that these measurements do not specifically describe the variable factors of the environment need not deter us any more than the fact that genotypic measurements do not specify the underlying biochemical processes. Indeed, this joint measure should ultimately provide a basis for better understanding physical limits in the environment as well as physiological control by the genotype."

2.1.2.3.1.3.3. The gene pool as a measure of environmental index

The most critical comparison between two varieties is obtained when both are always grown together at the same environments (locations and years). Such paired comparisons allow direct comparisons of two varieties over a range of environmental conditions. However, variety trials rarely contain the same entries over sites and years. The list of entries in the trials often varies from year to year because new entries are included as they become available and those with poor performance are deleted from further consideration. The substitution of entries in a series of trials results in unbalanced designs, and procedures for statistical analysis of balanced data cannot be used (McIntosh, 1983). This greatly reduces the flexibility needed to compare advanced germplasm with current commercial varieties over a period of time. Since new entries are being introduced annually, it is fruitless to retain the poor entries, and delay testing new entries, merely to maintain balance over a series of trials. Thus, imbalance will exist in most series of germplasm evaluation trials, and statistical analyses must accommodate this challenge.

Pedersen, Everson and Grafius (1978) developed the concept of a gene pool base as a means of measuring environmental indexes. They referred to a gene pool as a sample of genes representative of currently acceptable or commercially grown germplasm for a specific geographic area. The mean yield of all entries grown at a location is used as an index of the environment, and the precision of the experiment is increased whenever the gene pool is adapted within the area being tested.

In any year or at any location, the particular entries in the sample will vary somewhat, but as long as they are representative of the population gene pool the sample (site) mean can be used as a basis for comparison. The rationale behind the gene pool concept is that it enables comparisons among varieties grown in different locations and even in different years. Thus, it removes the necessity of a constant set of entries for comparison purposes, allowing freedom and confidence in making selections and variety recommendations over a range of yield levels. Pedersen et al. (1978), working with wheat (Triticum aestivum L.) found that limited additions and deletions to the gene pool over years and sites did not affect the average reaction to the environment. The gene pool mean can be used as an assessment of the environmental index in regression analyses.

2.1.2.3.2. Biological limitations

2.1.2.3.2.1. Cultivar response to environmental factors

Knight (1970) discussed problems of the biological interpretation of results from regression studies. In studies where only one factor of the environment is varied, and where that one factor is precisely controlled, it has commonly been found that the genotypic response to increased levels of an environmental factor show optima (Knight, 1970). An optimum would probably occur for any factor that was varied over a sufficient range. Thus, the relationship over the complete environmental range might be curvilinear. In linear regression analysis low yields arising from sub- and super-optimum levels of a factor are juxtaposed and the highest yields are obtained at the optimum level of the factor in question. This is particularly important where physical factors such as plant density, fertilizer levels, moisture levels, etc., are used to create different environments at a particular location.

Extrapolation of genotype response to environments beyond the range of environments used in the experiment should be approached with caution. If the results have been obtained covering super- optimal environmental conditions, then extrapolation of the regression line will be misleading as it would imply yields higher than those obtained at the optimum. However, in field situations super-optimum conditions may not always be encountered and the response is confined to the sub-optimal parts of the response curve (Knight, 1970; Snoad and Arthur, 1976). Deviation from linear regression is then not likely to be large except as a result of experimental error (Knight, 1970). In many experimental situations, therefore, the linear regression technique adequately describes the behaviour of genotypes over a range of environments, and upward extrapolation of the regression line may have some meaning. The degree to which any demonstrated linearity can be extrapolated to other environments can only be determined experimentally.

2.1.2.3.2.2. Prediction of response across environments or generations

From a practical point of view it would be valuable if plant response to a range of environments could be predicted from existing GE interaction data. Freeman (1973) stressed that one must not fail to recognize the conditional nature of much of the inference from linear regression. Because the mean yield of all varieties is used as a measure of the environmental index, results of stability analysis by regression techniques depend upon the particular varieties and environments studied. Varieties are not stable in some absolute sense but they are merely more stable than the rest of those under test, the tests having been conducted in a given set of environments. It is usually assumed that environments are random, and this may be so, but the varieties tested rarely are. Therefore, inferences should be confined to the set of varieties used in the experiment and should not be generalized (Freeman, 1973; Lin et al., 1986). However, when very good linearity is found by regressing results from different generations of inbred lines on midparent means predictions across generations are remarkably good (Freeman, 1973; Jinks and Perkins, 1970).

Environments are usually assumed to be random and so the regression technique can be used for predicting performance over environments (locations and years). The use of results for prediction of response depends on how far the environments used may be regarded as a random sample of all environments to be encountered. Particular attention should be paid to those environmental factors, whether natural or deliberately imposed, that are likely to determine the response of the materials to those conditions under which they will ultimately be grown (Perkins and Jinks, 1968).

For the regression technique to have high predictive value across environments, the major part of the GE interaction should be accounted for by linear regression with little or no significant deviation from linearity.

The extent to which differences among linear regressions account for GE interactions may be tested by the joint regression analysis. Essentially this analysis partitions, orthogonally, the variation which can be ascribed to GE interaction effects into an item measuring heterogeneity of regressions (GE linear) and a residual item. Where only the heterogeneity mean square is significant, against an appropriate error item, it is possible to predict the phenotypic response of each variety, within the limits of sampling error, from its linear regression on the environmental index (Breese, 1969; Gray, 1982; Jinks and Perkins, 1970; Samuel, Hill, Breese and Davies, 1970). Should both the heterogeneity and residual items prove to be significant, however, then the usefulness of any predictions will depend solely upon the relative magnitude of these two mean squares. The heterogeneity item should be re-tested against the residual item to determine whether it accounts for a significant proportion of the GE interaction variance. If it does the linear model will retain considerable predictive value for the varieties considered, though clearly the model will not be entirely satisfactory, since a significant amount of the variation due to GE interactions remains unaccounted for. If, by contrast, only the residual item is significant it means that either no relationship or no simple relationship exists between the varieties and the environments. More often than not, however, both items prove to be significant (Hill, 1975).

The conditions making for linearity of regression are very difficult to determine. One set of characters has frequently been found to give linear regressions, while other characters measured on the same set of varieties have not (Freeman, 1973). Fripp and Caten (1971) found that the selection of a subset of environments changed the relation between mean performance and both the linear and non-linear components of stability.

Jinks and Perkins (1970) presented evidence that predictions of the slope parameter (regression coefficient) can be made both across environments and across generations.

On the other hand, Williams (1975) examined the yield of strawberries (Fragaria spp) using regression techniques and concluded that, since different regression coefficients are obtained with the same material grown in a range of locations and years, predicting responses of varieties to untried environments using these regression techniques is a "hazardous procedure". Earlier, Witcombe and Whittington (1971) had concluded that in practice there are often wide deviations from linearity and using regression techniques to characterize response of varieties is "an over-simplification".

2.1.3. The contribution of individual varieties to GE interaction

Several alternative statistical approaches to the analysis of GE interactions have been reported. One approach partitions the total variation due to GE interactions into components assignable to individual varieties. Several methods have been proposed for making this partition (Plaisted, 1960; Plaisted and Peterson, 1959; Shukla, 1972; Wricke, 1962) and each produces a slightly different parameter. The contribution of each variety to the GE interaction is used as a measure of its stability.

2.1.3.1. Mean variance component for pairwise GE interaction

Plaisted and Peterson (1959) made an early attempt to measure the stability of individual varieties. They presented a technique for estimating the relative magnitude of the contribution of each variety to the GE interaction component of variance. The portion of variety-environment component contributed by a single variety was used as a measure of variety dependability.

The procedure is as follows:-

(i) a combined analysis of variance is computed for all varieties over environments. If the GE interaction is significant, the succeeding steps are followed;

(ii) a combined analysis of variance over all environments is computed for each pair of varieties. If there are v varieties, there will be v(v-1)/2 analyses and each variety occurs in v-1 pairs.

(iii) an estimate of variety-environment variance (σ^2_{VE}) is obtained for each pair of varieties.

(iv) an arithmetic mean of the σ^2_{VE} estimates is obtained for all pairs of varieties having one common member. There will be v-1 estimates in each mean. The mean of the estimated σ^2_{VE} having variety i in common represents the relative contribution of variety i to the GE interaction and is the stability measure for that variety. Considering such an analysis in n environments and r replicates, and with two varieties i and i' , the interaction sum of squares is:-

$$(\sigma^2_{VE})_{ii} = \Sigma_j \frac{(Y^2_{ij.} + Y^2_{i'j.})}{r} - \frac{(Y^2_{i..} + Y^2_{i'..})}{nr} - \Sigma_j \frac{(Y_{ij.} + Y_{i'j.})^2}{2r}$$

$$+ \frac{(Y_{i..} + Y_{i'..})^2}{2nr}$$

Summing this for the ith variety over all v-1 values of i, and multiplying by (2r/v), the relative contribution of variety i, (σ^2_{VE}), can be expressed as:-

$$(\sigma^2_{VE})_i = \Sigma_j Y^2_{ij.} - (v/n)\Sigma_j Y_{ij.}Y_{.j.} - (1/n)Y^2_{i..}$$

$$+ (2/vn)Y_{i..}Y_{...} + (1/v)\Sigma_i \Sigma_j Y^2_{ij.} - (1/vn)\Sigma_j Y^2_{i..} \quad .$$

Variety stability is inversely proportional to the attributable to that variety. The variety with the smallest mean value would be the one that contributed least to GE interactions and, thus, would be considered the most stable variety in the tests.

Baker (1969) used a similar approach in assessing stability of hard red spring wheat varieties. Pairwise analysis of locations has been used by other investigators to estimate the contribution of individual locations to GE interactions (Shorter, Byth and Mungomery, 1977).

The problem with Plaisted and Peterson's (1959) approach is that it is very cumbersome. If a large number of varieties are tested this would call for a large number, v(v-1)/2 , of analyses. However, nowadays large numbers of analyses can be handled by the use of computers.

Plaisted (1960) presented an alternative procedure in which one variety is deleted from the entire set of data and the GE interaction variance from this subset is the stability index of that variety. The larger the contribution of variety i to the GE interaction, the smaller will be the estimate of the subset interaction component of variance. Plaisted (1960) found that this method produced the same results as that of Plaisted and Peterson (1959) but with less computational effort.

2.1.3.2. Ecovalence

Wricke (1962) proposed that the relative contribution of a variety to the GE interaction sum of squares be used as a measure of its stability. The value of the stability parameter, termed 'ecovalence' (W_i) for the ith variety is calculated according to the formula:-

$$W_i = \Sigma_j Y_{ij}^2 - (2/v)_j Y_{ij} Y_{.j} + (1/v^2)_j Y_{.j}^2 - (1/n)(Y_{i.} - Y_{..}/v)^2$$

where, Y_{ij} is the performance of the ith variety in the jth environment ($i=1,2,...,v$; $j=1,2,...,n$);

$Y_{i.}$ is the sum of the ith variety over all n environments;

$Y_{.j}$ is the sum of the jth environment over all v varieties; and

$Y_{..}$ is the grand total.

The summation of this equation over all varieties gives the total GE interaction sum of squares. This expression can be re-written as:-

$$W_i = \sum_j [(Y_{ij} - Y_{.j}/v)^2 - 1/n(Y_{i.} - Y_{..}/v)^2]$$

$$= \sum_j [Y_{ij} - (Y_{.j}/v - Y_{..}/vn) - (Y_{i.}/n - Y_{..}/vn) - Y_{..}/vn]^2 .$$

In terms of model (1),i.e.

$$Y_{ij} = \mu + G_i + E_j + (GE)_{ij} + e_{ij} ,$$

$W_i = \sum_j (GE)_{ij}^2$, i.e., the GE interaction effects for the ith variety over all environments. The stability of a variety is inversely proportional to the GE sum of squares (ecovalence) which is attributed to that variety.

The parameter of Wricke (1962), ecovalence, is related to the parameters of Eberhart and Russell (1966), but as a single parameter appears potentially less informative (Jowett, 1972; Luthra and Singh, 1974). In reality the approach of Wricke (1962) assigns an index to a variety on the basis of its deviations from a regression line of unity; i.e., ecovalence is the sum of deviations due to a variety's regression being different from unity plus deviations from its own regression (Langer et al., 1979).

2.1.3.3. Stability variance

Shukla (1972) felt that the characterization of genotypic response on the basis of regression coefficients may not be very effective when only a small proportion of the GE interaction sum of squares can be attributed to heterogeneity among the regressions. Thus he proposed a method of estimating a component of GE interaction corresponding to each genotype as a better measure of genotype stability. This approach is similar to that of Plaisted and Peterson (1959) and Wricke (1962). The contribution of individual genotypes to the overall GE interaction is measured and the variance of the interaction deviations, **stability variance** (σ^2_s), is used as a measure of genotypic stability.

In the general model (1),

$$Y_{ij} = \mu + G_i + E_j + (GE)_{ij} + e_{ij} ,$$

the stability variance of genotype i (σ^2_{si}) is defined as the variance over environments of $(GE)_{ij} + e_{ij}$. This can be expressed as:-

$$\sigma^2_{si} = v \textstyle\sum_j s^2_{ij}/(v-1)(n-1).$$

For v genotypes in n environments, the unbiased estimate of the stability variance for the i<u>th</u> genotype (σ^2_{si}) is calculated as follows (Shukla, 1972):-

$$\sigma^2_{si} = \frac{1}{(n-1)(v-1)(v-2)} \left[v(v-1)\textstyle\sum_j (Y_{ij} - \bar{Y}_{i\bullet} - \bar{Y}_{\bullet j} + \bar{Y}_{\bullet\bullet})^2 - \sum_i \sum_j (Y_{ij} - \bar{Y}_{i\bullet} - \bar{Y}_{\bullet j} + \bar{Y}_{\bullet\bullet})^2\right] ,$$

where, Y_{ij} is the mean of the i<u>th</u> genotype in the j<u>th</u>

environment, and the remaining terms are the corresponding means defined by the dot-sum notation.

The significance of the stability variance is determined by approximate F-tests using the pooled error term from the combined analysis of variance, i.e.,

$F = \sigma^2_{si}/\sigma^2_o$, with (v-1) and vn(r-1) degrees of freedom, and σ^2_o is the pooled error mean square and r is the number of replicates in a trial (Shukla, 1972). This method can be applied for testing the homogeneity of all the variances or any pair of them.

Shukla (1972) defined a genotype as stable if its stability variance (σ^2_{si}) is not significantly different from within environmental variance (σ^2_o). Shukla's (1972) definition of stability coincides with Tai's (1971) definition of average stability (α_i=0;λ_i=1). This definition implies that the performance of a genotype is the sum of additive genotypic effect, additive environmental effect and random error without any GE interaction.

The stability variance is a function of two genotype-specific parameters. High stability variance arises from failure of the genotype's performance to have a regression slope of unity relative to the environmental index and/or from poor fit of the linear regression (high deviations from regression). Moll et al (1978) found that high stability variance could be attributed to high environmental variance associated with a genotype or to a low average degree of correlation of the genotype with the others tested. Any genotype exhibiting perfect correlation with the others would be associated with the minimal value of σ^2_s. Conversely, those genotypes that fail to conform to the predominating pattern of values across environments would have low average correlation to the overall GE variance. Thus, the most stable types are those which exhibit a consistent advantage or disadvantage relative to the environmental index. These types, when subjected to regression analysis, have slopes near one (b=1) and small deviations of observed values from those predicted by the sum of the environmental index and the average main effect of the genotype. Any genotype exhibiting larger than average environmental variance or failing to perform in proportion to the others will appear to be unstable. Isleib (1986 - personal communication) found the average degree of correlation to be the primary determinant of stability variance in a set of 15 soybean [Glycine max (L.) Merr.] breeding lines.

The main advantage of this method is that, unlike regression techniques, there is no need for large numbers of environments and hence it can be used to handle large numbers of genotypes. It also takes into account pairwise correlations between genotypes and the large numbers of individual analyses can be handled with the use of computers.

Lin et al., (1986) showed that the statistics of Plaisted (1960), Plaisted and Peterson (1959), Shukla (1972), and Wricke (1962) are equivalent. However, while the other statistics are merely index numbers, σ_s^2 is an unbiased estimate of the variance of genotype i.

Some of the problems of using a genotype's contribution to the total GE interaction as a measure of its stability are that:-

(i) the contribution of a genotype to GE interaction does not necessarily bear any relationship to its agronomic desirability. This is particularly true in a heterogeneous group set. In fact, genotypes that possess special characteristics (e.g. drought resistance, etc.,) maybe the largest contributers to GE interaction in a set of genotypes deficient for such a characteristic (Francis and Kannenberg, 1978);

(ii) the magnitude of the individual variety's GE interaction does not provide information on the response pattern over the range of test environments, information that is vital for making variety recommendations;

(iii) it is difficult to have low GE interactions if varieties are tested over a wide range of environments; and

(iv) a low GE interaction is not desirable in practice because it is often associated with low performance in good environments.

2.1.4. Multivariate techniques

Lin et al (1986) recommended a multivariate approach on the argument that the different stability parameters estimate different types of stability and it is difficult to reconcile the different stability parameters into a unified conclusion. They concluded that the basic reason for this difficulty is that a genotype's response to environments is multivariate yet the parametric approach tries to transform it to a univariate problem via a stability index.

Multivariate techniques are essentially an extension of the univariate technique. They have been suggested and applied as potential tools for studies on GE interactions and genotypic adaptation (Freeman, 1973; Hill, 1975; Lin et al., 1986). Hill (1975) summarized the purpose of multivariate analysis in terms of the analysis of GE interactions as follows: first, to assess the simultaneous effects of a number of environmental factors when these can be measured and rank them in order of importance by determining how much of the observed variation is accounted for by each individual factor, or composite factor derived therefrom, and secondly, to maximize differences between varieties (or environments) relative to differences within environments (or varieties). According to Seal (1964) the end-result is the "parsimonious summarization of a mass of observations".

Some of the multivariate techniques that have been used in studies of GE interactions are as follows:-

2.1.4.1. Principal component analysis (PCA)

Principal component analysis (PCA) was used by Goodchild and Boyd (1975), Okuno, Kikuchi, Kumagai, Okuno, Shiyomi and Tabuchi (1971), Suzuki (1968), and Suzuki and Kikuchi (1975) in studying variety adaptability. Freeman and Dowker (1973) applied two-way PCA to data recorded from a series of yield trials in carrots (*Daucus carota*) after the joint regression analysis had been only partially successful in explaining the observed GE interactions. As a result they were able to demonstrate the importance of site x year and density effects upon the yield differences between varietal groups. But they concluded that, in this experiment, the use of PCA to partition treatment effects had supplied no additional information beyond that obtained from the analysis of variance. Perkins (1972) gave a somewhat similar conclusion from a PCA of GE interactions in *Nicotiana rustica*. They compared PCA with linear regression and got similar results.

2.1.4.2. Pattern analysis

Mungomery, Shorter and Byth (1974) showed that pattern analysis methods were a useful alternative means of studying the performance of large sets of varieties over environments, using soybean data. Pattern analysis is a general term encompassing the use of both cluster analysis and ordination to examine data structure (Byth *et al*., 1976).

2.1.4.2.1. **Cluster analysis**

In cluster analysis an attempt is made to find similarities between clusters on the basis of measurements on the individuals of a cluster. The first attempt to do this was by Abou-El-Fittouh et al (1969) who used cotton data to identify regions of similar genotypic adaptation (minimal GE interaction). Mungomery et al (1974) used cluster analysis to group genotypes on the basis of similarity. Similarity was defined as euclidian distance between genotype in the space whose co-ordinate axes were environments and whose origin was zero.

Genotypes can also be grouped according to stability responses (Chuang-Sheng Lin and Thompson, 1975; Ghaderi, Everson and Cress, 1980; Hanson, 1970; Lin et al., 1986). Hanson (1970) proposed that relative stability be measured as the euclidian distance (D) of a variety from the linear response of an ideal stable variety in a stability space whose co-ordinate axes are environments and whose origin is the genotypic mean. The linear response of the stable ideal was defined simply as an arbitrary, or experimentally derived, fraction of the average linear response of all varieties, i.e., as a fraction of the environmental index. Hanson (1970) also proposed that comparative stability between varieties (an indication of similarity of stability responses) be measured as euclidian distance between varieties in the same space as defined for the determination of relative stability.

Relative stability gives full information on the relative magnitude of variation among varieties but no information on similarity. Comparative stability provides full information on similarity of response but no information on mean differences or magnitude of variation.

Hanson's (1970) stability measure is similar to Wricke's (1962) but takes into account regression. In terms of the parameters of model (1), the ecovalence of the ith variety (W_i) is $\Sigma_j (GE)^2_{ij}$, while Hanson's (1970) parameter is D_i, where

$$D^2_i = \sum_j (GE)^2_{ij} + (1-\alpha)E^2_j$$

and is not the same as Tai's (1971), being defined as the minimum observed value of $(1+\beta_i)$. A value of $\alpha=1.0$ makes the parameter the same as Wricke's (1962).

Johnson (1977) proposed a model which gives information on varietal similarity in terms of mean differences, relative stability and comparative stability.

There are various methods of calculating similarities, and these may affect the clusters obtained. The unicriterion methods of measuring similarity include (i) **euclidian distance** (Abou-El-Fittouh et al., 1969; Hanson, 1970; Johnson, 1977; Mungomery et al., 1974), (ii) **standardized distance** (Abou-El-Fittouh et al., 1969; Fox and Rosielle, 1982), (iii) **dissimilarity index** (Lin, 1982, Lin and Thompson, 1975), and (iv) **correlation coefficient** (Guitard, 1960; Habgood, 1977). In contrast to unicriterion clustering, the multicriterion procedure developed by Lefkovitch (1985) uses a cluster algorithm that permits more than one measure of pairwise relationship. Lefkovitch (1985) defined dissimilarity of genotypes by three measures: (i) the mean over environments, (ii) the variance across environments, and (iii) among environments pattern distance.

Lin et al (1986) stated that the advantage of cluster analysis is that although genotypes are grouped based on a specific data set, the relative relationship among genotypes can be independent of any specific set of data analysed. This avoids the inferential limitation of regression techniques. In whatever way it is done, clustering allows subsets of genotypes to be described by the characteristics of the separate groups, although not directly in terms of stability (Lin et al., 1986). If a well known variety is included in the test, it can be used as a paradigm for the other varieties in the same subset. These varieties may be regarded as having the overall characteristics of this variety and extrapolation for them to a much wider range of environments than those tested may be possible (Lin and Binns, 1985). However, cluster analysis gives full information on similarity but no information on varietal stability.

Clustering that involves only the regression coefficients would reveal similarities in stability (comparative stability) whereas clustering that includes means reveals similarities including both average performance and stability (genotypic similarity) [Johnson, 1977].

2.1.4.2.2. Factor analysis

Grafius and Kiesling (1966) used factor analysis methods to construct orthogonal vectors representing environmental effects, and thus predict genotypic responses in terms of these vectors.

Multivariate techniques have not been widely used in plant breeding and in the analysis of GE interactions. This is mainly because, unlike univariate and regression methods, they lack simplicity and biological relevance (Hill, 1975). Often, multivariate methods yield answers giving insight into particularly complex situations, and this may well happen in the study of GE interactions (Freeman, 1973; Hill, 1975). However, there is the very real danger that biological relevance will be sacrificed for statistical pedantry (Hill, 1975). Thus univariate and regression techniques will continue to be important in studies of GE interactions, variety adaptation and stability.

2.1.5. Other methods

2.1.5.1. Coefficient of determination (r^2)

Pinthus (1973) proposed the use of the coefficient of determination (r^2), which measures the proportion of a variety's production variation that is attributable to linear regression, as an index of production stability to environments. Bilbro and Ray (1976) stressed that a logical parameter for stability is one which measures the dispersion of performance (e.g. yield) around the regression line and is, therefore, related to the predictability and repeatability of performance within environments. The mean square deviations from regression (S_d^2) and coefficient of determination (r^2) are well suited for this purpose (Bilbro and Ray, 1976; Fakorede and Mock, 1978; Langer et al., 1979; Nguyen, Sleper and Hunt, 1980). Bilbro and Ray (1976) and Langer et al (1979) favoured the use of r^2, instead of S_d^2, as a measure of stability on the basis that it not only provides a measure of variation but it is easily calculated, independent of units of measure, easily interpreted and differences between r^2 values can be statistically tested. High r^2 values indicate a good fit of the linear regression line, and hence high predictability and repeatability of performance. However, since the environmental sum of squares contributes to the regression sum of squares in linear regression analysis, coefficients of determination may be large and misleading (Moll, et al., 1978)

2.1.5.2. Range indexes

For practical plant breeding purposes it would be desirable to have a simpler method than regression analysis for evaluating the response characteristics of large numbers of genotypes in preliminary trials. As simpler methods, Langer, et al (1979) proposed two indexes related to the ranges in productivity of varieties as crude measures of production response. The first (denoted R_1), is the difference between the minimum and maximum (extreme) yields of a variety in a series of environments. The second (denoted R_2), is the difference between the yields of a variety in the lowest and best production environments.

In a study of yield variation in oats, Langer, et al (1979) obtained very high and highly significant, correlations between linear regression coefficients (b values) and R_1 (r=0.90), and R_2 (r=0.76) values. This indicated that varieties could be screened for regression response indexes simply by utilizing the ranges in variety means. R_2 would be somewhat more utilitarian than R_1 because, to estimate the former, only two fairly extreme environments would be required. This would be particularly useful in preliminary trials where there are often large numbers of varieties to be tested and consequently only few locations can be used.

2.1.5.3. Percentage adaptability

St-Pierre, Klinck and Gauthier (1967) proposed the use of '**percentage adaptability**' as a measure of wide adaptation. They defined the 'percentage adaptability' of a variety to be the number of environments in which its performance is better than the mean performance of all varieties, expressed as a percentage of the number of environments in which it is tested. On the other hand, Campbell and Lafever (1977) suggested that the proportion of environments in which a variety does not differ significantly from the highest yielding variety in that environment provides an easily calculated measure of variety potential.

2.2. Stability as a breeding objective

2.2.1. Mechanisms of yield stability

Stability of performance is a breeding objective difficult to achieve. The causes of yield stability are often unclear, and physiological, morphological and phenological mechanisms that impart stability are diverse (Heinrich, Francis and Eastin, 1983). It is important for the plant breeder to recognize the traits that confer wide or specific adaptation and stability, so that selection procedures can be tailored to meet the breeding objectives. It is equally important to understand the interactions between plant traits related to adaptability and the prevailing range of environmental conditions. Where such interactions are in favourable directions, stability in production can also be realized (Gotoh and Chang, 1979).

Mechanisms of yield stability fall into three general categories: (i) genetic heterogeneity, (ii) developmental plasticity, and (iii) stress resistance.

2.2.1.1. Genetic heterogeneity

Allard and Bradshaw (1964) suggested that heterozygous and heterogeneous populations offer the best opportunity to produce varieties which show small GE interactions. They equated stability with the term '**well-buffered**' and defined two types of buffering, namely, individual buffering and population buffering.

Individual buffering is a property of a single genotype and denotes the ability of that genotype to produce an acceptable phenotype over a wide range of environmental conditions. **Population buffering** is a property of the population and derives from the possession by a genetically diverse population, a sufficient number of different genotypes each adapted to a somewhat different range of environments. A homogeneous variety (heterozygous or homozygous) must depend largely on individual buffering to achieve stability over a range of environments, whereas a heterogeneous variety may use both individual and population buffering for this purpose. The use of genetic mixtures (e.g. three-way or double-cross hybrids, synthetics, composites, multilines, etc.,) rather than homogeneous (e.g. pure lines, single-cross hybrids, etc.,) varieties has been suggested as a means to reduce GE interactions. In maize, Eberhart and Russell (1966), Funk and Anderson (1964), Rowe and Andrew (1964), and Sprague and Federer (1951) reported that heterogeneous populations (three-way and double-cross hybrids) tended to have better yield stability (less GE interactions) than homogeneous (single-cross hybrids) populations. However, Eberhart and Russell (1969), and Lynch, Hunter and Kannenberg (1973) found that some single-crosses were just as stable for yield as the best double-crosses, and that the stability seemed to be mainly a property of the inbred parents. Thus high yielding stable single-cross maize hybrids can be developed by appropriate selection techniques, including recurrent selection for yield and prolificacy in the parental populations (Eberhart, 1969).

2.2.1.2. Developmental plasticity

Mechanisms which contribute to developmental plasticity include rapid phenological development, tillering, progressive flowering associated with the indeterminate growth habit and prolificacy. Prolificacy has been found to be associated with yield stability in maize. Russell and Eberhart (1968) found that test-cross maize hybrids developed from a group of prolific inbreds had lower deviations from regression (higher stability) than an analogous group developed from non-prolific inbreds. Similarly, Cross (1977), and Prior and Russell (1975) reported that prolific hybrids grown at different population densities were more consistent in yielding ability than single-eared hybrids.

Yield component compensation can be a major mechanism of yield stability. A reduction in one yield component may be compensated, to varying degrees, by increases in other yield components, and depending on temporal development of stress, there is a tendency to stabilize yield (Heinrich et al., 1983). Some components of yield are mutually compensatory and may be so for their stability also.

Saeed and Francis (1983) reported that stability for, the yield component, seed number was crucial for yield stability in grain sorghum [*Sorghum bicolor* (L.) Moench]. Morishima and Oka (1975) reported that stability of panicle length was strongly and positively correlated with yield stability in rice (*Oryza sativa*). This suggested that stability during panicle development results in yield stability. Thus, stability for yield components such as seed number, seed weight, etc., is equally important and should be considered in breeding stable varieties. Stability for quality characteristics, such as protein quality, etc., should also be of important consideration in field crops.

2.2.1.3. Stress resistance

Stress resistance (e.g. to drought, pests, diseases, etc.,) is important for yield stability, particularly in subsistence agriculture. To the farmer, strong demand for a variety may depend more upon minimization of performance problems in stress or low productivity environments than upon wide adaptability (Gotoh and Chang, 1979). Joppa et al (1971) suggested that large deviations from regression were due to specific instabilities such as disease susceptibility in particular environments. They found many cases of interactions between genotypes and specific pathogens in wheat. Photoperiod insensitivity is one of the important factors responsible for wide adaptability of Mexican wheats.

2.2.2. Inheritance of stability

Genotype-environment interactions are as much a function of the genotype as they are of the environment and so are partly heritable (Hill, 1975). In a diallel experiment, Eberhart and Russell (1966) found genetic differences among single-cross maize hybrids for stability. The variation among single-crosses in the average performance suggested additive gene action for the regression coefficients and to a lesser extend in the deviation mean squares. Stability seemed to be partly a property of the inbred parent lines. Scott (1967) showed that yield stability in maize is genetically controlled and that selection can be effective. Reich (1968) also reported genetic differences among single-crosses for stability parameters in sorghum. By using appropriate male parents on the same male-sterile female parents, it was possible to choose hybrids with limited deviation mean squares. Bucio-Alanis et al (1969), and Perkins and Jinks (1968) also demonstrated that production stability is heritable in crop plants.

In a later study, Eberhart and Russell (1969) found that stability in maize, as measured by deviation mean square, appeared to involve all types of gene action. They concluded that stability, as measured by the deviation from regression on the environmental index, seems to be inherited in a more complex fashion and hence, it will have to be determined for each genotype in extensive evaluation trials over a wide range of environmental conditions. Estimates of the less important regression coefficient would require fewer but widely differing environments. Thus potentially useful genotypes must be grown in an adequate number of environments covering a wide range of possible environments occurring in the region selected for the breeding programme in order to identify stable, high yielding genotypes by regression techniques (Eberhart, 1969; Russell and Prior, 1975).

eGama and Hallauer (1980) compared the relative stability of grain yield among maize hybrids produced from selected and unselected lines. Yields of selected hybrids were significantly greater than yields of unselected hybrids, but both groups of hybrids had equal numbers of stable hybrids when the stability parameters b and S_d^2 were considered. Selection based on yield did not seem to enhance stability for yield. They concluded that selection of hybrids for mean yield across environments should be emphasized first, and then the relative stability of the elite hybrids over environments determined. However, results might have been different if previous selection had been based on stability rather than on yield alone.

2.2.3. Selection for stability and adaptation response

2.2.3.1. Selection sites

The site of early generation selection plays a major role in determining the range of adaptation (Johnson, 1977). The adaptability and stability of crop plants is generally assessed at the advanced testing stage without any previous directed selection for wide adaptation or stability. Material previously screened at one or two environments is evaluated over a number of environments (locations and years) during the advanced testing stages. Progress in yield improvement would be facilitated if selection for wide adaptability and/or stability could be conducted in early generations. However, in early generations of a breeding programme there are often large numbers of genotypes to test and consequently only few locations can be used. Testing for stability using regression techniques is, therefore, not feasible.

Varieties with wide adaptation should come from a selection programme which permits the best expression of genes for wide adaptation (St-Pierre et al., 1967). It seems logical to assume that a variety selected under environments which favour optimum expression of genes for adaptation should possess the morphological and physiological plasticity required for wide adaptation. The generally accepted theory of selection for wide adaptation is that selection should be made under the environmental conditions where the variety is expected to be grown. Selection and evaluation should be conducted under a wide range of conditions to ensure wide adaptation of the genotypes (Bilbro and Ray, 1976). If the number of testing sites must be limited (as is almost always the case), one should choose sites, for making selections, that are highly correlated with other sites in the region where the varieties are to be grown. Site similarity can be determined by cluster analysis or by calculating the correlation coefficients of the variety mean yield at each location with the corresponding mean yields at each of the other locations. A high correlation indicates that a site is representative of the others. Specific adaptation may be desirable for stabilizing yield at locations not representative of the region in general (Campbell and Lafever, 1977).

Where rainfall (both amount and distribution) is a major environmental factor, early and late dates of planting can often be used to obtain extra environments at each location (Eberhart and Russell, 1966). Similarly, management factors primarily responsible for differences in performance, such as plant densities, fertilizer application rates, etc., can be used to increase the number of environments possible from a fixed number of locations, and at the same time provide a greater range of environmental conditions (Easton and Clements, 1973; Eberhart and Russell, 1966; Fakorede and Mock, 1978; Heinrich et al., 1983; Luthra and Singh, 1974; Snoad and Arthur, 1976).

2.2.3.2. Selection techniques

It is possible to select for yield stability and adaptation using two contrasting environments (locations or seasons). Oka (1967) called this '**disruptive seasonal selection**'. The wide adaptation of Mexican wheat varieties (which do well in Canada and Asian countries) is attributable to an aggregate of characters including insensitivity to photoperiod, stiff straw, high response to nitrogen, resistance to many rusts, etc. According to Borlaug (1965), at CIMMYT (Mexico), two generations of segregating materials were grown and selected each year to accelerate the breeding programme. The plants were grown in a winter nursery at sea level in north-west Mexico at latitude 27°N and in a summer nursery at 2 800m altitude near Mexico city at latitude 18°N.

Selection for the best material at each of the test sites in turn resulted in a gene pool of high-yielding and widely adapted lines for final selection. This approach (also known as '**shuttle breeding**') is an example of disruptive seasonal selection.

2.2.3.3. The different concepts of stability

Plant breeders generally agree on the importance of good phenotypic stability, but there is much less accord on the most appropriate definition of stability and on a statistical measure of stability in variety trials. As the review of literature indicates, the concept of stability has been defined in a variety of ways, each dependent on the method used to estimate it. Plaisted (1960), Plaisted and Peterson (1959), Shukla (1972), and Wricke (1962) based their measure of stability upon the contribution of a genotype to the total GE interaction sum of squares. Finlay and Wilkinson (1963) defined stability solely in terms of the regression coefficient (b values), whereas Hanson (1970) devised a composite measure of stability which combines the contribution of the ith genotype to the GE interaction sum of squares with its response to environmental change. Others (Eberhart and Russell, 1966; Perkins and Jinks, 1968; Tai, 1971) opt for two separate stability parameters, the regression coefficient (b) values being considered in conjunction with a measure of the scatter of points about this fitted regression line (mean square deviations from regression). By contrast, Bilbro and Ray (1976), and Breese (1969) argued against the incorporation of the regression coefficient values into measures of stability, preferring instead to reserve the term for those measurements of unpredictable irregularities in the response to environments as provided by the deviations from regression (S_d^2) and coefficient of determination (r^2). They interpreted the regression coefficient (b) as an additional parameter reflecting the response, adaptation or sensitivity of a genotype to the level of productivity of the environments.

In addition to the stability parameters considered above, more simple methods have been proposed, such as the use of the differences between the maximum and minimum yields of a variety over a range of environments (Langer, et al., 1979), comparisons of the ranks of a variety in different environments (Thomson and Cunningham, 1979), or relating the yields to the highest yielding variety (Sepahi, 1974; Jensen, 1976), etc. These methods may be worthy of attention for practical plant breeding and much more information on their efficiency is desirable. Others (Lin et al., 1986) have argued that the regression technique and other parametric approaches are inadequate and proposed the use of multivariate techniques in studies of GE interactions. Hill (1975) cautioned on the use of multivariate techniques, and most of them are measures of similarity rather than stability or adaptability and hence have not been widely used.

Becker (1981a,b) distinguished two basic concepts of phenotypic stability. He used the term '**biological concept**' of stability to characterize a genotype which has a constant performance in all environments. Such a genotype has minimal variance over different environments. This type of stability is in agreement with the concept of homeostasis and is equivalent to what Finlay and Wilkinson (1963) referred to as maximum phenotypic stability (b=0). Lin et al (1986) referred to it as **Type 1 stability.** This type of stability is not desirable because the variety does not respond to improved growing conditions. Researchers and farmers prefer varieties which always realize the yield expected at the level of production of the respective environment, i.e., varieties with GE interactions as small as possible. Becker (1981a,b) referred to this as an '**agronomic concept**' of stability, and is equivalent to Lin et al's (1986) **Type 2 stability.**

When the biological concept of stability is applied, the variance of performance over environments is usually used as a statistical measure. Different statistical measures have been proposed for assessing the agronomic concept of stability. The widely used regression technique may be regarded as a combination of biological and agronomic concepts of stability, since the regression coefficient is strongly associated with variance (Becker, 1981a,b). The mean square deviation from regression indicates the phenotypic stability according to the agronomic concept of stability and should be as small as possible in a variety. The regression coefficient measures the response of the variety based on the biological concept of stability. Its desired value depends upon the special situation and the breeder's objectives (Becker, 1981a). However, Lin et al (1986) considered the regression coefficient to be a measure of Type 1 stability or the biological concept of stability only if its desired value is zero (b=0). All other values of the regression coefficient (b<1.0 or b>1.0) measure Type 2 stability or the agronomic concept of stability. Also, Lin et al (1986) considered the deviation mean square to be a measure of a different type of stability (**Type 3 stability**) which is not equivalent to the agronomic concept of stability. They considered Type 3 stability to be the least attractive. However, the deviation mean square provides useful additional information when used in conjunction with the regression coefficient. Many reports are available which indicate that the deviation mean square is highly correlated with the parameters which measure Type 2 or the agronomic concept of stability.

2.2.3.4. Interrelationships among stability parameters

The regression coefficient is a suitable measure of production response in the performance of a genotype to changes in environmental productivity. Eberhart and Russell

(1966) found that maize hybrids with regression coefficients less than unity (b<1.0) usually had mean yields below the grand mean suggesting a positive relationship between yield and the response index (b). There are many other reports on significant, high positive correlations between mean yields and regression coefficients (Baihaki, Stucker and Lambert, 1976; Cross, 1977; Eagles and Frey, 1977; Eberhart, 1969; Fatunla and Frey, 1974; Finlay and Wilkinson, 1963; Gonzalez-Rosquel, 1976; Langer et al., 1979; Jensen and Cavalieri, 1983; Perkins and Jinks, 1968; Saeed and Francis, 1983).

If the stability of a variety is assumed to be a measure of how well the observed response agrees with the expected response derived from the linear regression equation (variety predictability), then the parameters r^2 and S_d^2 that measure dispersion of points around the best fitting linear regression are the best measures of stability (Bilbro and Ray, 1976; Breese, 1969; Langer et al., 1979). Several authors (Becker, 1981a,b; Campbell and Lafever, 1977; Easton and Clements, 1973; Langer et al., 1979; Luthra and Singh, 1974; Nguyen et al., 1980) found the stability parameters ecovalence (W), coefficient of determination (r^2), mean square deviation (S_d^2), and stability variance (σ_s^2) to be significantly and highly correlated with one another, when large numbers of varieties are grown in a sufficiently broad environmental range. This suggests that any of them should be a satisfactory parameter for measuring stability.

On the other hand, low or no significant correlations have been reported between either the response parameter (b) or mean productivity (e.g. mean yield) with the various parameters (W, r^2, S_d^2 or σ_s^2) that measure stability of production (Becker, 1981a,b; Easton and Clements, 1973; Gray, 1982; Langer et al., 1979; Nguyen et al., 1980). This suggests that production stability indexes and production response indexes (b and/or mean performance) can be selected independently. Thus, it should be possible to obtain varieties with any combination of production response and production stability and, hence, it should be possible to accomplish breeding for high yield, high response (b>1.0) and stability (Langer et al., 1979).

Becker (1981a,b), Easton and Clements (1973), Freeman (1973), and Marquez-Sanchez (1973) discussed the interrelationships among the different stability parameters. Becker (1981b) discussed the existence of strong correlations between (i) ecovalence (W) and mean square deviation (S_d^2), (ii) r^2 and W, (iii) r^2 and S_d^2, and (iv) variance and the regression coefficient (b).

The strong correlation between ecovalence (W) and S_d^2 can be understood if W is partitioned in order to distinguish between the relative importance of various components. The ecovalence can be partitioned into two components, (1) a component which is a function of linear regression $[(b-1)^2\sigma_E^2]$

and (2) a component which is the variance of the deviations (S_d^2), i.e.,

$$W = (b-1)^2 \sigma_E^2 + S_d^2 ,$$

with σ_E^2 being the variance of the effect of the environment (E). The component $(b-1)^2 \sigma_E^2$ is usually small, and thus the magnitude of the ecovalence (W) and S_d^2 are highly correlated. The strong negative correlation between S_d^2 and r^2 is due to the relatively large variability of S_d^2 when compared with variance (σ^2) for $S_d^2 / \sigma^2 = 1-r^2$ (Becker, 1981a,b), with σ^2 being the variance of the performance values (Y_{ij}) of the ith genotype.

The high correlation between variance (σ^2) and regression coefficient (b) is similarly explained. The variance can be partitioned as follows (Becker, 1981b):-

$$\sigma^2 = \sigma_E^2 + 2(b - 1) \sigma_E^2 + (b - 1)^2 \sigma_E^2 + S_d^2$$

The contribution of σ_E^2 may be disregarded because it is common to all genotypes. Differences in variance (σ^2) are chiefly dependent on differences in the term $2(b -1) \sigma_E^2$, a linear function of the regression coefficient (b). Consequently, σ^2 and b should be highly correlated (Becker, 1981a,b).

From the observed correlations, Becker (1981b) concluded that:-

(i) the regression coefficient is equivalent to the variance as a measure of stability according to the biological concept of a stable genotype (one with a constant yield);

(ii) the mean square for deviations from regression is equivalent to the ecovalence and r as a measure of stability according to the agronomic concept of a stable genotype (one with a yield which is predictable from the levels of productivity of the environment); and

(iii) the use of different concepts of stability will lead to different ranking of genotypes, for the parameters belonging to the different concepts are not correlated. This agrees with the findings of other researchers, as already discussed above.

To comprehensively characterize a genotype's reaction to environments, it is necessary to use statistical measures that assess both the biological and agronomic concepts of stability (Becker, 1981a). Since various parameters are strongly associated, a breeder may use, alternatively, either:

(1) variance (σ^2) and ecovalence (W), which are most directly related to the underlying concepts; or

(2) the regression coefficient (b) and the coefficient of determination (r^2), which are independent of the scale of measurement; or

(3) b and mean square deviations from regression (S_d^2), which are best known and perhaps most graphic (Becker, 1981a).

2.2.4. The potential usefulness of the linear regression technique in plant breeding

Despite its imperfections, the regression technique, as elaborated by Eberhart and Russell (1966), and Perkins and Jinks (1968), is the most widely used method of stability analysis today (Becker, 1981a). It has the twin merits of simplicity and biological relevance, attributes which are lacking from multivariate techniques (Hill, 1975). Hill (1975) concluded that the main advantage of the regression technique derives from its proven ability to reduce complex interactions to a series of orderly, linear responses. Like every other model it will sometimes fail.

The linear regression technique is versatile and in many instances it can be used to adequately describe and predict the relative performance of genotypes in varying environments or generations other than those sampled experimentally. It can be useful in characterizing genotypes as to their range of adaptation and in identifying unusual performance at specific sites (Campbell and Lafever, 1980). Genotypes with specific adaptations can be readily identified when varieties are tested over a wide range of environments. Varieties that respond to environmental change and, therefore, are likely to give satisfactory returns to high management levels (e.g. high rates of inputs such as fertilizers, etc.,) can be identified.

Selection based on yield over a number of environments automatically eliminates varieties which are specifically adapted to certain conditions. Generally, genotypes which perform better than the site mean at the lower yield potential levels are discarded because of poor performance in high yield potential areas. Similarly, varieties that do well in good environments but very poorly in, for example, drought environments could be inadvertently discarded because of mediocre overall means over all test sites. Also, selection based on mean yields alone gives no information on predicted response to certain environmental changes and may result in erratic performance across varying environments (Schilling, Mozingo, Wynne and Isleib, 1983).

The regression technique can be used heuristically to isolate, and hence identify, the differential responses of genotypes to various physical factors of the environment (Hill, 1975). Factors that limit yield are reflected in each variety's response in relation to the site mean yield. Where the linear regression coefficient accounts for all or most of the GE interactions, it is a convenient measure of the relative stability of a genotype to the environment (Perkins and Jinks, 1968). For example, if yield at low yielding sites is reduced by drought stress, then the regression coefficient values are indicators of relative performance of varieties under drought conditions. Thus varieties resistant to specific environmental stresses can be identified. Graphing of regression lines is particularly effective in emphasizing the actual trend of varietal performance to a range of environments. Locations can also be identified that have consistently high, low, intermediate or variable yield ranges over years.

The regression analysis may assist the breeder in determining the level of stress under which tests of varieties should be conducted. If the point of convergence of regression lines occurs at an environmental index below that commonly encountered by end-users of these genotypes, then the ranking of genotypes under good sites will not differ from their ranking in poor sites, and yield testing should continue at good sites where heritabilities of characters are frequently higher and expected rates of gain greater (Eagles and Frey, 1977). If a cross over of responses or regressions occurs near the middle of the range of environments encountered by end users of genotypes then selection should occur in those environments despite the increase in uncontrolled variability that may be found in such environments (Eagles and Frey, 1977).

While mean yield remains a critical measure of genotypic superiority, given the prevalence of GE interactions, utilization of the response (adaptation) and stability parameters provides additional information which, in conjunction with mean yield and other desirable agronomic and quality characteristics should enhance the effectiveness of genotype comparisons in making selections and in making variety recommendations. Thus, the linear regression approach should be regarded as an addition to the breeder's armoury of techniques which, if used correctly, should facilitate the decision-making process in a particular breeding programme. It is, however, not the plant breeder's panacea. It does not offer a complete solution to problems associated with GE interactions (Hill, 1975). The final measure of adaptation and/or stability will depend upon how well the variety is accepted by farmers over a period of time and locations.

3. MATERIALS AND METHODS

3.1. Experimental procedure

The material for this study was comprised of 25 commercial single-cross maize hybrids developed by different seed companies (Appendix Table 1). These hybrids were chosen to represent a range in grain yield potential and genetic background. The 25 maize hybrids were evaluated in yield trials grown at eight locations (sites) in the main maize producing areas of Michigan (Table 2). The trials were conducted during the 1985 and 1986 summer seasons. Each year-location combination was considered as an environment. Thus there were 16 year-location environments representing varying edaphic and climatic (e.g. temperature, soil moisture, season length, etc.,) conditions (Appendix Tables 2 to 9).

A 5 x 5 simple lattice design with four replications was used at each site. Each plot consisted of one row 9 m (30 ft) long and rows were spaced 90 cm (36 inches) apart at the Michigan State University (M.S.U.) field plots, and 11.1 m (37 ft) long and spaced 75 cm (30 inches) apart at all the other sites.

In 1985 fifty seeds were machine-planted in each plot. In 1986 sixty seeds were machine-planted in each plot and subsequently thinned to 50 plants per plot giving a plant population equivalent to about 60,500 plants per hectare (24,200 plants/acre) at the M.S.U. field plots, and 58, 875 plants per hectare (23, 550 plants/acre) at the other locations.

Standard cultural practices were employed in each test site. One set of experiments at Montcalm county and those at Cass county received supplementary irrigation during the growing season. The whole plots were machine-harvested using a plot combine harvester.

At all sites, data were collected from each plot for the following agronomic traits:-

(1) number of root lodged plants, and converted to percentage root lodging;

(2) number of stalk lodged plants, and converted to percentage stalk lodging;

(3) plant stand at harvest;

(4) shelled grain weight (field weight) in lbs/plot; and

(5) grain moisture content (%).

The field weights (lbs/plot) were converted to metric tons per hectare (t/ha) and adjusted to 15.5% moisture by the formula:-

$$Gw = \frac{Fw(100 - m) \times 4.54}{84.5 \times \text{plot area}},$$

where, Gw = grain weight (t/ha) adjusted to 15.5% moisture,

Fw = field grain weight (lbs/plot), and

m = percentage moisture in grain at harvest.

In the M.S.U. field plots extra data were recorded on:-

(i) ear height (cm): measured as the distance from the soil at the base of the plant to the top ear-node;

(ii) plant height (cm): measured as the distance from the soil at the base of the plant to the tip of the centre spike tassel; and

(iii) number of ears per plot, and converted to number of ears per 100 plants.

Table 2. Site information

Site	Mean yield (t/ha)‡	I_j	Yield potential
Branch County	9.46	1.4	high
Cass County (irrigated)	10.16	2.1	high
Montcalm County (irrigated)	9.59	1.5	high
Huron County	8.25	0.2	intermediate
Ingham County (M.S.U.)	7.43	-0.6	intermediate
Monroe County	8.25	0.2	intermediate
Kalamazoo County	6.03	-2.0	low
Montcalm County (dryland)	5.27	-2.8	low

‡four-year (1981-84) mean yield.(Source: Rossman, Dysinger, Chamberlain, Leep and Westerhof, 1984)

I_j = environmental index (= site mean minus grand mean).

3.2. Statistical analyses

Analyses of variance and Student-Newman-Keuls' (SNK) multiple range tests were used to evaluate the agronomic traits within each location. The combined analysis of variance procedure of Comstock and Moll (1963) was adopted to test the significance of location, year, genotype, and first- and second-order interactions for grain yield. The year and location effects were assumed to be random while genotypic effects were considered fixed.

For grain yield, an analysis of variance over environments was performed taking each year-location combination as a separate environment. Significance of the GE interaction was tested using a pooled error term from the individual analyses of variance. A significant GE interaction was obtained and formed the basis for stability analyses.

The relative stability and adaptation responses of the hybrids for mean grain yield across environments were determined using the regression technique of Eberhart and Russell (1966) and by GE interaction sum of squares partitioning according to the method of Shukla (1972). Regression coefficients (b values) and mean square of deviations from regression (S_d^2) were estimated for each hybrid according to the model:

$$Y_{ij} = \mu + b_i I_j + s_{ij}$$

where, Y_{ij} is the mean grain yield of the $i\underline{th}$ variety in the $j\underline{th}$ environment ($i=1,2,....,v$; $j=1,2,.....,n$);

μ is the mean of the $i\underline{th}$ variety over all environments;

b_i is the regression coefficient that measures the response of the $i\underline{th}$ variety to varying environments;

s_{ij} is the deviation from regression of the $i\underline{th}$ variety at the $j\underline{th}$ environment;

I_j is the environmental index; and

v (=25) is the number of varieties, and n (=16) is the number of environments.

Two measures of the environmental index (I_j) were used:
(i) the mean yield of all 25 entries at a particular site was used as an index of the productivity of the environment, giving rise to a non-independent measure of I_j and a biased estimate of the regression coefficient, and
(ii) the mean yield of all entries excluding the values of the entry regressed was used as an independent measure of I_j giving rise to an unbiased estimate of the regression coefficient.

The hypothesis that each regression coefficient did not differ from unity was tested by the t-test using a pooled error estimate. The correlation between the biased and unbiased estimates of the regression coefficients were calculated using both rank and actual values.

The deviation mean square (S^2_{di}) for each entry was estimated as follows:

$$S^2_{di} = [\Sigma_j s^2_{ij}/(n-2)] - \sigma^2_e/r \quad ,$$

where σ^2_e is the estimate of the pooled error and r is the number of replications. The significance of the deviations from regression for each entry was tested by an approximate F-test using the pooled error term from the individual analyses of variance; i.e.

$$F = (\Sigma_j s^2_{ij}/n-2)/\text{pooled error.}$$

Coefficients of determination (r^2) were obtained from the linear regression analyses.

The stability variance (σ^2_s) proposed by Shukla (1972) was unbiasedly estimated for each entry using the formula:

$$\sigma^2_{si} = \frac{1}{(n-1)(v-1)(v-2)} [v(v-1)_j (Y_{ij} - Y_i. - Y._j + Y..)^2$$

$$-\Sigma_i \Sigma_j (Y_{ij} - Y_i. - Y._j + Y..)^2] \; ,$$

where, Y_{ij} is the mean grain yield of the i<u>th</u> entry in the j<u>th</u> environment;

$Y_i.$ is the mean of the i<u>th</u> entry over all n environments;

$Y._j$ is the mean of the jth environment over all v entries; and

$Y..$ is the grand mean.

The significance of each σ_{si} was determined by an approximate F-test using the pooled error term as denominator; i.e.

$$F = \sigma_{si}/\text{pooled error.}$$

The average correlations between each entry and all others were estimated by calculating simple correlations among means over environments. Simple correlation coefficients among mean grain yield, biased and unbiased estimates of regression coefficients, mean square deviation from regression, coefficients of determination, stability variances and average correlations between entries were computed using both variety ranks and the actual figures.

The mean grain yields across environments and regression coefficients were used as measures of adaptability (production response). The parameter estimates S^2_d, r^2 and σ^2_s were used to assess relative phenotypic stability.

All analyses were performed using an IBM Personal Computer AT and MSTAT programs.

4. RESULTS AND DISCUSSION

The quality of the individual experiments were very good, with coefficients of variation ranging from 1.98 to 6.03%, for the grain yield results (Appendix Tables 10 to 25). The coefficients of variation for root and stalk lodging were considered too high and results for these traits will not be discussed in this study.

The lattice design did not increase efficiency over a RBD in 7 trials and the relative efficiency was below 110% in all but one of the remaining trials, where it was 125% (at the Ingham County trial in 1985).

The combined analysis of variance for grain yield is shown in Table 3. Year effects were not significant for grain yield. The location effect was significant ($p<0.05$) indicating variability among locations for yield. The highly significant year x location (Y x L) interaction suggests that location effects were variable between years. Thus, each year-location combination can be treated as a separate environment.

The first order interactions (G x L and G x Y) and second order interaction (G x Y x L) were all highly significant (Table 3). The significant second-order

Table 3. Combined analysis of variance for grain yield of 25 maize hybrids grown at eight locations in 1985 and 1986 in Michigan

Source of variation	d.f.	SS	MS
Years (Y)	1	2.92	2.92 ns
Locations (L)	7	639.86	91.41*
Y x L	7	143.87	20.55**
Hybrids (G)	24	211.08	8.80**
G x Y	24	18.13	0.76**
G x L	168	99.64	0.59**
G x Y x L	168	61.50	0.37**
Environments‡	(15)	786.66	52.44**
G x E	(360)	179.27	0.50**
Pooled error	1008	30.24	0.03

*,** significant at the 0.05 and 0.01 probability levels, respectively.

‡an environment is a year-location combination.

interaction indicates that G x L interaction was inconsistent over years. This suggests that it is necessary to repeat yield trials over locations and years. The significant G x Y x L interaction indicates that each individual experiment is unique and environmental conditions differentiating these trials cannot be grouped according to years or locations. This lends credibility to the use of each year-location combination as a separate environment. The GE interaction was highly significant (Table 3) and was made up mostly of G x L interaction effects (55.6%). The G x Y and G x Y x L interactions contributed 10.1% and 34.3%, respectively, to the total GE interaction. The relative magnitudes of the σ^2_{GL} and σ^2_{GY} emphasize the need to replicate more over locations than years in order to obtain more precise estimates of yield.

Although there were highly significant ($p<0.01$) differences among entries for mean yield across sites (Table 3), considerable difficulty would be involved in identifying the superior hybrids because of the significant GE interaction. Thus it would be necessary to evaluate the relative responses of the individual entries to varying environments.

Stability analysis is most meaningful if the environmental indexes have a wide range and a good distribution within the range (Russell and Prior, 1975). Site mean yield data in Table 4 indicates that these criteria were met reasonably well. The highly significant ($p<0.01$) environmental effect (Table 3) indicates significant variability among environments for yield. The site mean yields ranged from 7.06 t/ha at Kalamazoo County in 1985 to 12.60 t/ha at Montcalm County (irrigated trial) in 1986 (Table 4). This yield range was considered adequate for evaluating the yield stability and adaptation responses of the entries in this study.

Variations for mean grain yield among environments (locations and years) were caused primarily by differences in soil moisture, soil type and temperature during the growing season. Environments with high yield levels received ample rainfall or were irrigated. There was very poor stand establishment at Huron County in 1986.

Moll et al.(1978) noted that regression is a function of both (i) the responsiveness of entries to environments and (ii) the correlations of the responses of entries in different environments. For genotypes to provide reliable environmental indexes for each other, they should have highly correlated responses across environments. To test the validity of the environmental indexes, mean correlation coefficients ($\bar{r}$) were determined between each entry and all others over environments. The mean correlations among entries were very high and highly significant, and ranged from 0.75 to 0.95 (Table 5). Thus all entries provided an adequate

Table 4. Site mean yields of 25 maize hybrids grown at eight locations over two years (= 16 environments) in Michigan

Site	Year	Site mean yield (t/ha)	I_j	Classification‡
Kalamazoo County	1985	7.06	-3.39	low
Huron County	1986	7.83	-2.62	low
Kalamazoo County	1986	9.54	-0.91	low
Huron County	1985	9.92	-0.53	low
Ingham County	1986	9.95	-0.50	low
Montcalm dryland	1986	10.09	-0.36	low
Ingham County	1985	10.32	-0.13	intermediate
Montcalm dryland	1985	10.58	0.13	intermediate
Monroe County	1986	10.83	0.38	intermediate
Branch County	1986	10.98	0.53	intermediate
Branch County	1985	11.11	0.66	intermediate
Cass irrigated	1986	11.11	0.66	intermediate
Monroe County	1985	11.27	0.82	high
Cass irrigated	1985	11.82	1.37	high
Montcalm irrigated	1985	12.22	1.77	high
Montcalm irrigated	1986	12.60	2.15	high

‡arbitrary classification indicating environment productivity level.

grand mean yield = 10.45 t/ha.

Table 5. Mean grain yield across sites and estimates of adaptation and stability parameters for grain yield of 25 maize hybrids grown at eight locations in 1985 and 1986 in Michigan

hybrid number	mean yield (t/ha)	$b^{\dagger}$	b^{*}	r^2	S^2_d	σ^2_s	r
14	12.06 a†	0.99	0.99	0.86	0.32	0.33	0.92**
11	11.58 b	1.09	1.09	0.89	0.29	0.32	0.94**
15	11.41 bc	1.02	1.01	0.88	0.29	0.30	0.93**
4	11.33 bc	1.06	1.05	0.85	0.42	0.44	0.92**
10	11.29 bc	1.02	1.02	0.89	0.27	0.29	0.94**
7	11.16 c	1.02	1.01	0.88	0.30	0.32	0.93**
3	10.84 d	1.12	1.12	0.89	0.33	0.38	0.94**
20	10.84 d	0.75*	0.74*	0.80	0.28	0.44	0.89**
6	10.66 de	1.00	0.99	0.87	0.30	0.32	0.93**
24	10.66 de	1.06	1.06	0.83	0.51	0.53	0.90**
23	10.54 def	1.12	1.12	0.88	0.37	0.42	0.93**
1	10.48 def	0.96	0.94	0.72	0.78	0.80	0.83**
19	10.35 efg	0.82	0.80	0.77	0.43	0.52	0.87**
8	10.34 efg	1.01	0.98	0.65	1.20	1.23	0.81**
13	10.32 efg	0.96	0.95	0.86	0.30	0.31	0.92**
2	10.22 fgh	0.98	0.97	0.83	0.41	0.42	0.90**
16	10.07 gh	0.82	0.80	0.73	0.53	0.63	0.84**
25	10.02 gh	1.37**	1.38**	0.92	0.48	0.80	0.94**
12	9.90 hi	1.16	1.16	0.82	0.62	0.70	0.90**
9	9.88 hi	1.17	1.17	0.89	0.36	0.44	0.94**
17	9.67 i	0.94	0.93	0.89	0.22	0.25	0.94**
21	9.66 i	0.69*	0.67*	0.59	0.72	0.96	0.75**
22	9.56 ij	1.16	1.15	0.87	0.43	0.50	0.92**
5	9.34 jk	0.89	0.87	0.75	0.57	0.61	0.85**
18	9.13 k	0.82	0.81	0.91	0.11	0.20	0.95**

*,** b significantly different from 1.0 and r from zero at the 0.05 and 0.01 probability levels, respectively.

†means followed by the same letter not significantly different based on SNK multiple range test at the 0.05 probability level.

$b^{\dagger}$ = regression coefficient based on a non-independent I_j;

b^{*} = regression coefficient based on an independent I_j ;

r^2 = coefficient of determination based on a dependent I_j;

S^2_d = mean square deviation from regression;

σ^2_s = stability variance; and

r = mean correlation coefficients among entries.

measure of the environmental index for each other. The highly significant correlated responses of all entries to environments also suggest that GE interaction was mostly due to differences in responsiveness among the entries and hence regression analysis is expected to provide useful additional information.

To overcome the problem of the statistical dependence of the use of genotypic mean as a measure of the environment, the mean of all genotypes excluding the entry regressed (mean of the remainder) can provide an independent measure of the environment (Mather and Caligari, 1974). This gives an unbiased estimate of the regression coefficient. The bias resulting from the use of a non-independent measure of the environment (the mean of all entries including the mean of the entry regressed) can be examined by comparing biased and unbiased estimates of regression coefficients and calculating the correlation between them (Wright, 1976). The results in Tables 6 and 7 show that both the numerical and rank correlation coefficients between the biased and unbiased regression coefficient estimates were highly significant ($p<0.01$) and very high in value (0.999 and 0.994, respectively) indicating an almost perfect association between the regression coefficients and a negligible amount of bias. The regression coefficient values for individual entries were similar in relative magnitude and rank (Table 5) and it made little difference whether a dependent or

Table 6. Simple rank correlations among production response and stability parameters for grain yield of 25 maize hybrids grown at eight locations in Michigan in 1985 and 1986

	$b^{\ddagger}$	b^{*}	$r^{2\ddagger}$	r^{2*}	S_d^2	σ_s^2	r
y	0.19	0.21	0.14	0.14	-0.32	-0.30	0.20
$b^{\ddagger}$		0.99**	0.53**	0.50**	0.05	0.02	0.54**
b^{*}			0.56**	0.52**	0.02	-0.01	0.56**
$r^{2\ddagger}$				0.99**	-0.71**	-0.68**	0.98**
r^{2*}					-0.74**	-0.71**	0.98**
S_d^2						0.92**	-0.72**
σ_s^2							-0.72**

** correlation coefficient significantly different from zero at the 0.01 probability level.

y = mean grain yield across environments;

$b^{\ddagger}$ = regression coefficient using a non-independent I_j ;

b^{*} = regression coefficient using an independent I_j ;

$r^{2\ddagger}$= coefficient of determination using a non-independent I_j ;

r^{2*}= coefficient of determination using an independent I_j ;

S_d^2 = mean square deviation from regression;

σ_s^2 = stability variance; and

r = mean correlation coefficient among entries.

Table 7. Correlations among production response and stability parameters (based on actual figures) for grain yield of 25 maize hybrids grown at eight locations in Michigan during 1985 and 1986

	$b^{\ddagger}$	b^{*}	$r^{2\ddagger}$	r^{2*}	S^2_d	σ^2_s	r
$\bar{y}$	0.16	0.17	0.25	0.27	-0.20	-0.30	0.20
$b^{\ddagger}$		0.999**	0.58**	0.55**	-0.02	-0.01	0.54**
b^{*}			0.60**	0.57**	-0.05	-0.04	0.56**
$r^{2\ddagger}$				0.99**	-0.80**	-0.79**	0.98**
r^{2*}					-0.78**	-0.80**	0.98**
S^2_d						0.95**	-0.72**
σ^2_d							-0.72**

** correlation coefficient significantly different from zero at the 0.01 probability level.

$\bar{y}$ = mean grain yield across environments (t/ha);

$b^{\ddagger}$ = regression coefficient using a non-independent I_j;

b^{*} = regression coefficient using an independent I_j;

$r^{2\ddagger}$ = coefficient of determination using a non-independent I_j;

r^{2*} = coefficient of determination using an independent I_j;

σ^2_d = stability variance;

r = mean correlation coefficient among entries; and

S^2_d = mean square deviation from regression.

independent environmental measure was used. Thus, while the use of a non-independent environmental index does not satisfy the requirements of a regression analysis, it provides sufficiently reliable estimates of stability parameters. This is in agreement with results reported by Perkins and Jinks (1973) in *Nicotiana rustica* L., Snoad and Arthur (1976) in peas and Tan *et al* (1979) in smooth bromegrass (*Bromus inermis* Leyss.). Further discussion will be based on adaptation and stability analyses using a non-independent measure of the environmental index.

The rank correlation between mean yield across sites and the regression coefficient was very low (r=0.19) and non-significant (Table 6). This suggests that little or no relationship exists between grain yielding ability and the capacity to respond to environmental variations. Becker (1981a, b) and eGama and Hallauer (1980) reported similar results in maize. Other workers (Fatunla and Frey, 1974; Langer *et al*., 1979; Gonzalez-Rosquel, 1976), however, reported very high ($r > 0.90$) and significant correlations between mean yield and regression coefficients in oat lines. The positive sign of the non-significant correlation is in agreement with the findings of Eberhart (1969), and Eberhart and Russell (1966) who reported that maize hybrids with a regression coefficient less than unity usually had mean yields below the grand mean. The rank correlations between mean yield and stability parameter estimates (S^2_d, σ^2_s and r^2)

were all very low and non-significant (Table 6) indicating that selection based on yield might not enhance yield stability.

The rank correlations for the regression coefficients (b) with mean square deviations from regression (S^2_d), and b with stability variances (σ^2_s) were both near zero (r= 0.05 and r=0.02, respectively). This suggests that it should be possible to obtain maize hybrids with any combination of b and S^2_d or b and σ^2_s values. Similar results were obtained for yield in maize (Becker, 1981a, b), oat (Langer et al., 1979), orchard grass (Gray, 1982), tall fescue (*Festuca arundinacea* Schreb.), and wheat (Easton and Clements, 1973).

The rank correlation between S^2_d and σ^2_s was very high (r=0.92) and highly significant (Table 6) indicating that the rankings of entries by these two parameters are similar and that there is close similarity between the two parameters. Thus any one of them can be used in place of the other as a measure of stability. High stability variance (σ^2_s) can arise from (i) failure of a genotype to have a regression slope of unity to the environmental index, or (ii) from poor fit of the linear regression (high deviation from regression). Hybrids 20, 21 and 25 which had b values significantly different from unity had high values of σ^2_s which were also of much higher magnitudes than S^2_d values. All hybrids which had b values close to unity had S^2_d and σ^2_s values of similar magnitude. Thus when the b value is close to unity the magnitude of the stability variance depends chiefly on the magnitude of the deviation mean square and hence S_d^2 and σ_s^2 are highly correlated. Lin et al (1986) suggested that if the data does not fit linear regression or if residual mean square is significant then ecovalence or stability variance should be used and deviation mean square is not recommended. However, since S_d^2 and σ_s^2 are highly correlated Lin et al's (1986) suggestion does not seem to be valid in these data.

As expected, there were highly significant negative correlations between S_d^2 with r^2 (r= -0.71) and r^2 with σ_s^2 (r = - 0.68). The coefficient of determination is a measure of goodness of fit of the linear regression line and hence, as expected, a small r^2 value translates into large S_d^2 and σ_s^2 values. In this way r^2 values can be used as a measure of stability, and high r^2 values would be more desirable.

There was no significant correlation between mean yield across sites and mean correlations among varieties (Tables 6 and 7). The correlations between regression coefficients and r^2 with the mean variety correlations were highly significant indicating that the varieties that were highly correlated with the others or followed the general pattern of response had higher b and r^2 values. The highly significant negative correlations between $\bar{r}$ with S_d^2 (r= -0.72) and σ_s^2 (r= -0.72) indicate that the varieties that were less correlated with the others and hence did not follow the general pattern closely had higher values of S_d^2 and σ_s^2. These would be considered the most unstable while those that were highly correlated with the others had lower S_d^2 and σ_s^2 values (Table 8). Thus it is important to find out the underlying biological basis for any differences in stability of response so that varieties with specific desirable traits are not discarded on the basis of failure to follow the general pattern, which might not necessarily be the desirable one. However, on average, the varieties were all highly and significantly correlated with each other and so the parameter estimates S_d^2 and σ_s^2 should provide valid measures of relative stability. In this study, an entry with significantly high S_d^2 and σ_s^2 values would still be considered desirable if its high S_d^2 and σ_s^2 values are a result of desirable atypical behaviour.

4.1. Adaptation responses

The regression coefficient (b value) was used as a measure of adaptation response. The 25 hybrids used in this study responded differently to environments of varying levels of productivity. The regression coefficients ranged from 0.69 (for hybrid 21) to 1.37 (for hybrid 25). Two hybrids (20 and 21) had b values significantly less than unity (Table 8), indicating a lower than average response to varying environments. Only one hybrid (hybrid 25) had a b value significantly greater than unity (b=1.37), indicating an above average response to varying environments. All the other

Table 8. Mean grain yield across sites and estimates of adaptation and stability parameters for grain yield of 25 maize hybrids grown at eight locations in 1985 and 1986 in Michigan

hybrid number	mean yield (t/ha)	b	r^2	S_d^2	σ_s^2	$\bar{r}$
14	12.06a‡	0.99	0.86	0.32**	0.33**	0.92**
11	11.58b	1.09	0.89	0.29**	0.32**	0.94**
15	11.41 bc	1.02	0.88	0.29**	0.30**	0.93**
4	11.33 bc	1.06	0.85	0.42**	0.44**	0.92**
10	11.29 bc	1.02	0.89	0.27**	0.29**	0.94**
7	11.16 c	1.02	0.88	0.30**	0.32**	0.93**
3	10.84 d	1.12	0.89	0.33**	0.38**	0.94**
20	10.84 d	0.75*	0.80	0.28**	0.44**	0.89**
6	10.66 de	1.00	0.87	0.30**	0.32**	0.93**
24	10.66 de	1.06	0.83	0.51**	0.53**	0.90**
23	10.54 def	1.12	0.88	0.37**	0.42**	0.93**
1	10.48 def	0.96	0.72	0.78**	0.80**	0.83**
19	10.35 efg	0.82	0.77	0.43**	0.52**	0.87**
8	10.34 efg	1.01	0.65	1.20**	1.23**	0.81**
13	10.32 efg	0.96	0.86	0.30**	0.31**	0.92**
2	10.22 fgh	0.98	0.83	0.41**	0.42**	0.90**
16	10.07 gh	0.82	0.73	0.53**	0.63**	0.84**
25	10.02 gh	1.37**	0.92	0.48**	0.80**	0.94**
12	9.90 hi	1.16	0.82	0.62**	0.70**	0.90**
9	9.88 hi	1.17	0.89	0.36**	0.44**	0.94**
17	9.67 i	0.94	0.89	0.22**	0.25**	0.94**
21	9.66 i	0.69*	0.59	0.72**	0.96**	0.75**
22	9.56 ij	1.16	0.87	0.43**	0.50**	0.92**
5	9.34 jk	0.89	0.75	0.57**	0.61**	0.85**
18	9.13 k	0.82	0.91	0.11**	0.20**	0.95**

grand mean yield = 10.45

*,** b significantly different from 1.0 for the regression coefficients, from the pooled error mean square for the deviation from regression mean square and stability variance, and from zero for the mean correlation coefficients, at the 0.05 and 0.01 probability levels, respectively.

‡ means followed by the same letter not significantly different based on SNK multiple range test at the 0.05 probability level.

b = regression coefficient based on a non-independent I_j

r^2 = coefficient of determination based on a non-independent I_j

Table 8 (continued)

S_d^2 = mean square deviation from regression;

σ_s^2= stability variance; and

r = mean correlation coefficients among entries.

22 hybrids showed an average response to varying environments, with regression coefficients not significantly different from unity (Table 8). The mean grain yields across environments ranged from 9.13 t/ha (for hybrid 18) to 12.06 t/ha (for hybrid 14), with a grand mean of 10.45 t/ha (Table 8).

On the basis of both mean yield across environments and b values the 25 hybrids can be classified for adaptation into four distinct classes. Ten hybrids (1,3,4,6,7,10,11,14,15 and 24) were well adapted to the whole range of environments used in this study. They had b values not significantly different from unity and above average mean yields across environments. Their expected relative yield responses (Figs 4 to 7) are above average throughout the whole range of environments. Nine of these were among the top 10 hybrids in this study, on the basis of mean yield across environments. Six of these (4,7,10,11,14 and 15) had mean yield across environments significantly higher than the grand mean (Table 8). These ten hybrids would be selected if selection is based on two-year mean yields across eight sites.

Eight hybrids (2, 5, 8, 9, 12, 17, 18 and 22) were poorly adapted to all environments (Figs 8 and 9). They had b values not significantly different from unity and all but two (2 and 8) had across-environments mean yields significantly lower than the grand mean (Table 8). Thus on the basis of the

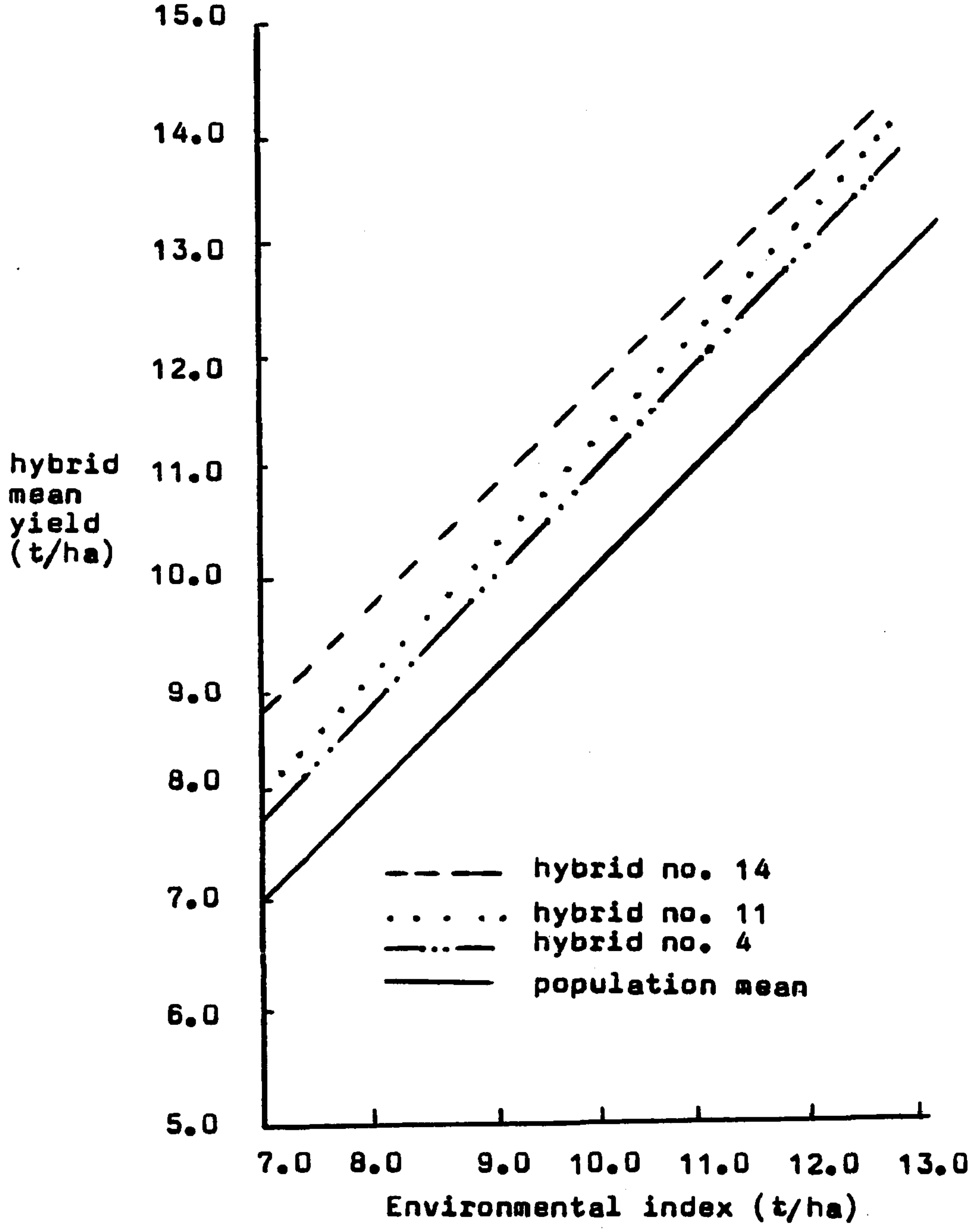


Fig 4. Yield responses of three maize hybrids well adapted to a range of environments

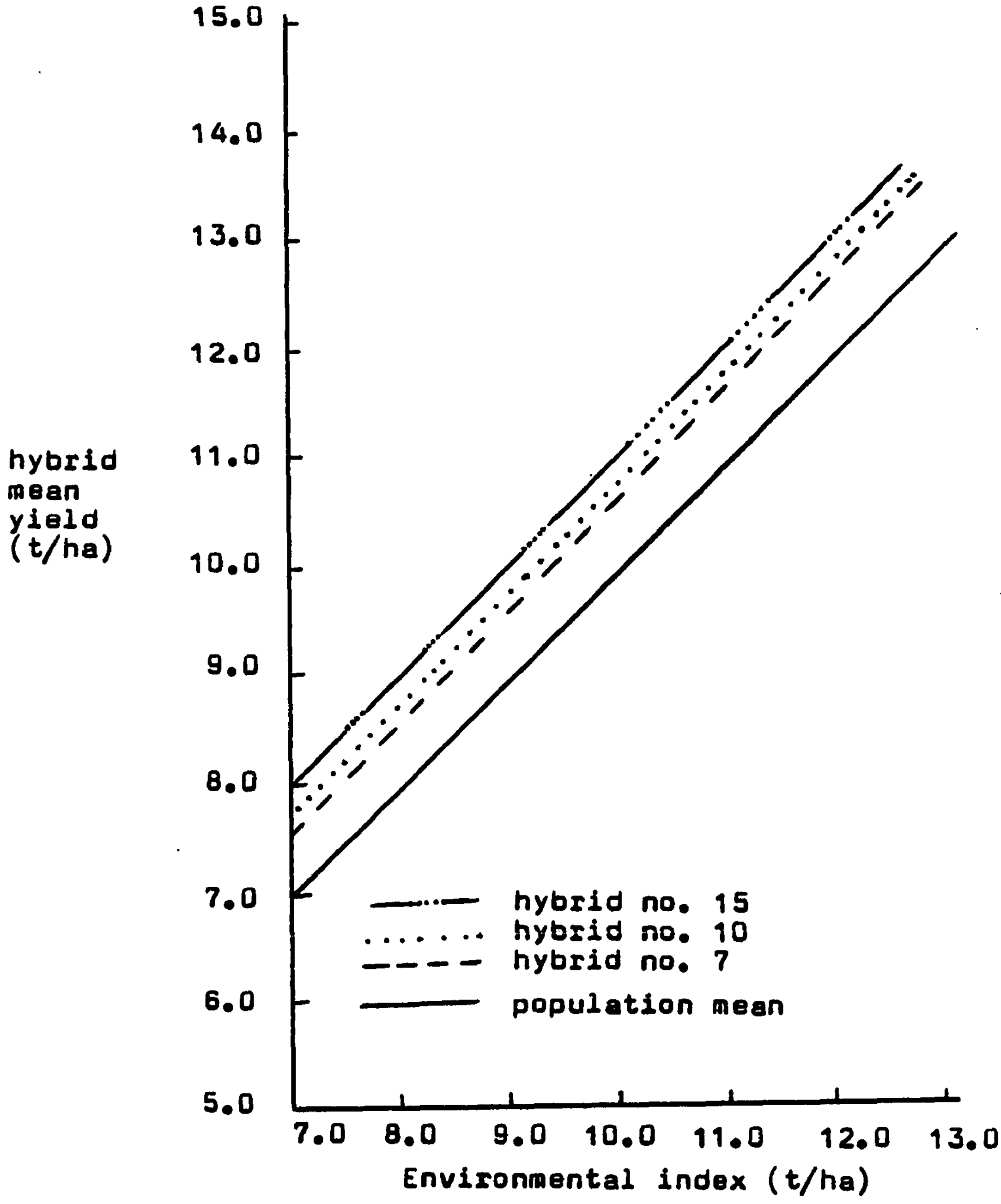


Fig 5. Yield responses of three maize hybrids well adapted to a range of environments

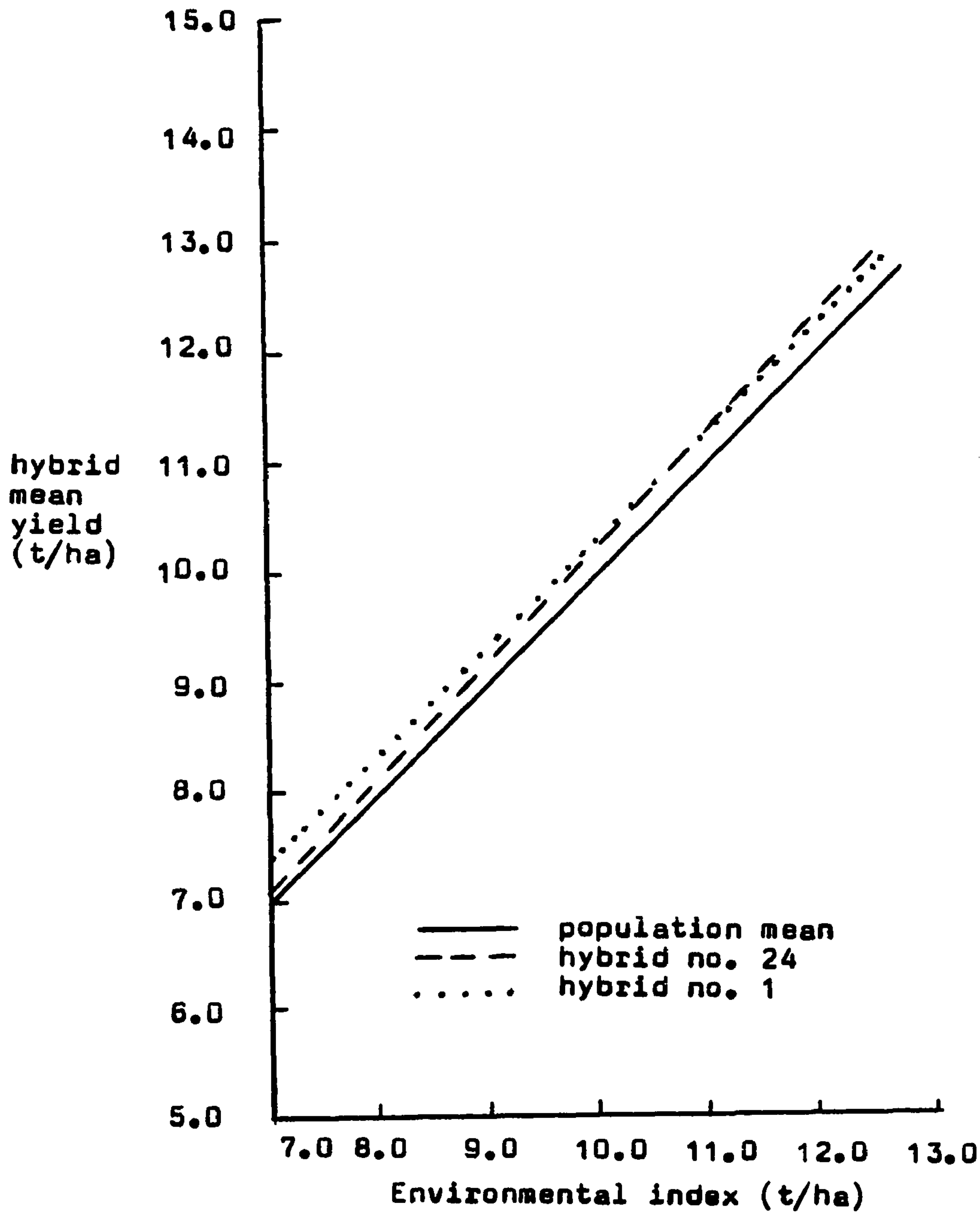


Fig 6. Yield responses of two maize hybrids well adapted to a range of environments

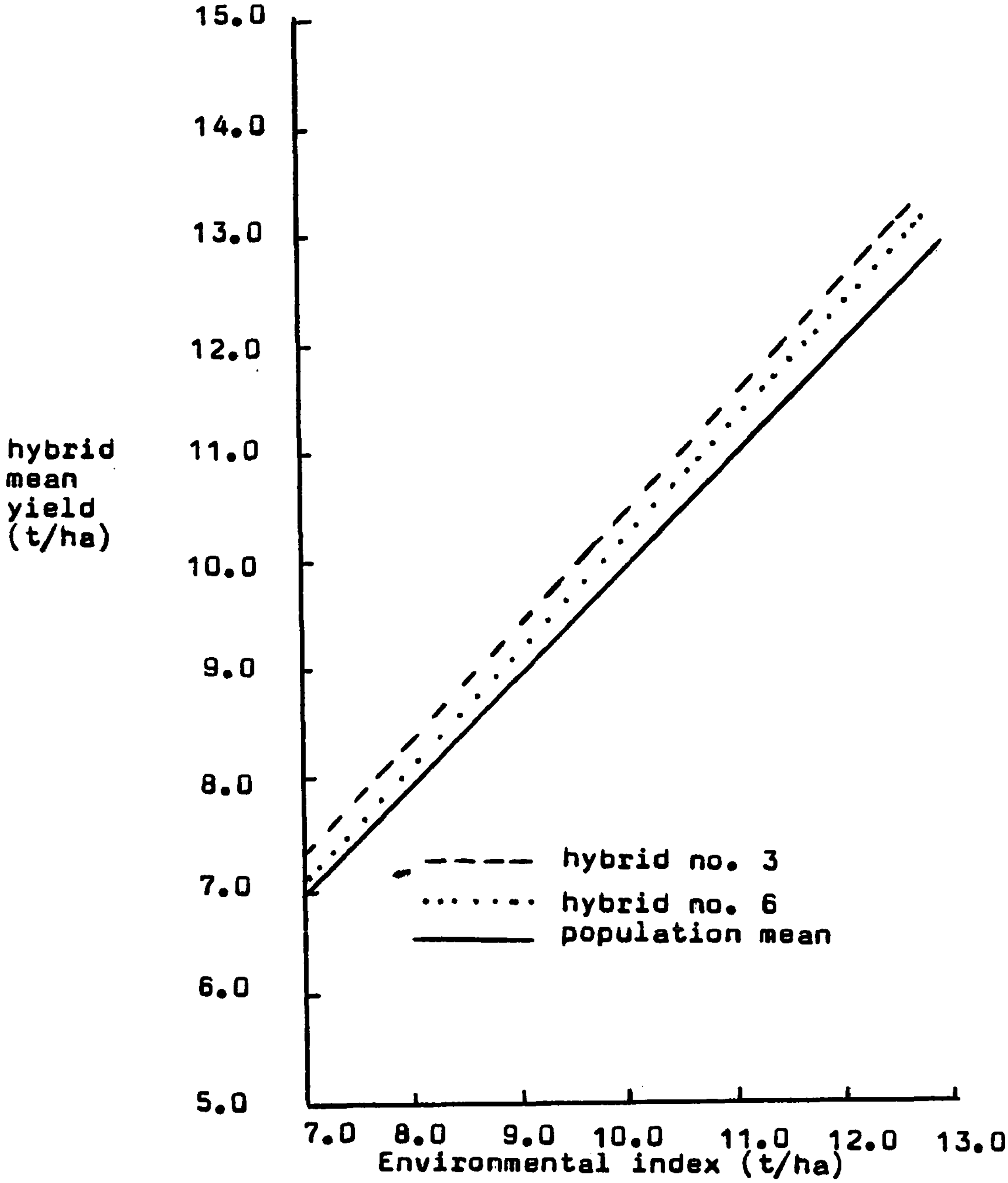


Fig 7. Yield responses of two maize hybrids well adapted to a range of environments

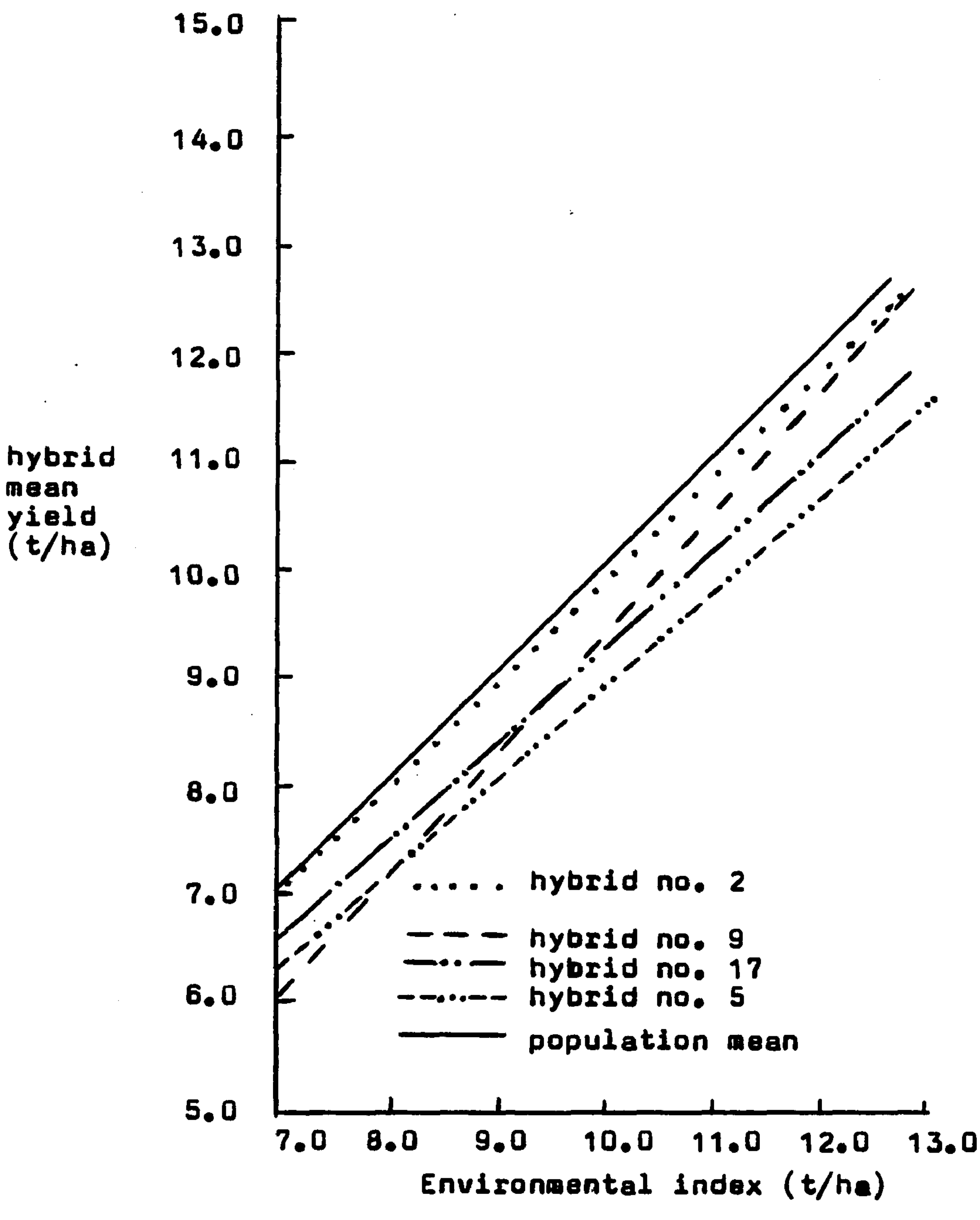


Fig 8. Yield responses of four maize hybrids poorly adapted to a range of environments

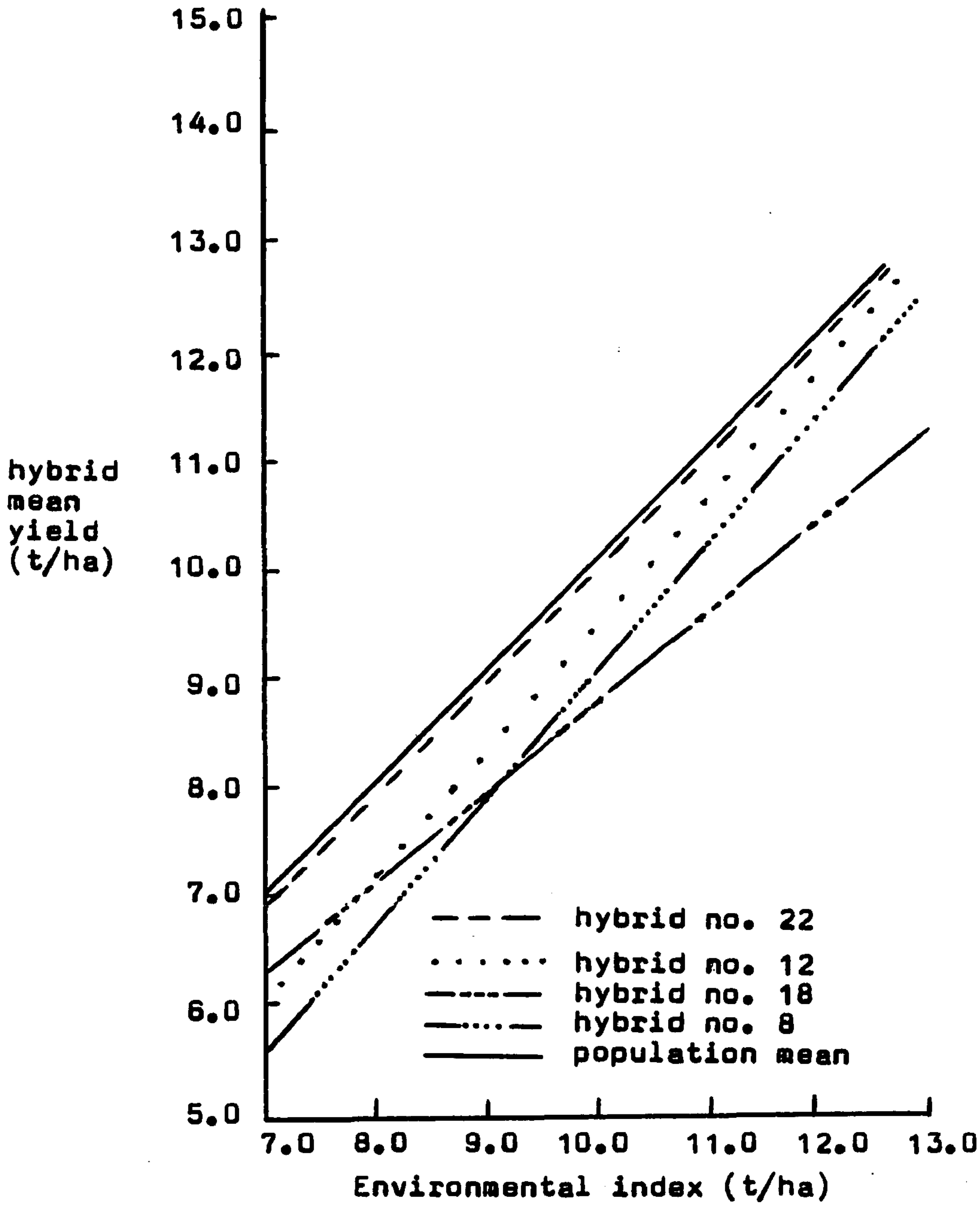


Fig 9. Yield responses of four maize hybrids poorly adapted to a range of environments

across-environments mean yield they could possibly be discarded.

Two hybrids (23 and 25) were poorly adapted to low-yielding environments but well adapted to high-yielding environments. Their expected relative response is to give below average mean yields in low-yielding environments and above-average yield response in high-yielding environments (Fig 10). Hybrid 23 with a b value of 1.12 had the capacity to utilize environments with a yield potential of about 10.0 t/ha and above (Fig 10) resulting in its above average mean yield across sites. On the basis of across sites mean yield alone, hybrid 23 could be selected. The unusually large and highly significant b value of hybrid 25 (b = 1.37) was primarily related to its low yield under low yielding environments and its ability to catch up with other entries in increasingly favourable environments. Its superiority was beyond a yield potential level of about 11.5 t/ha (Fig 10). It yielded below average for most of the environmental range resulting in below average mean yield across environments and on the basis of mean yield it would be discarded.

Five hybrids (13, 16, 19, 20 and 21) were specifically adapted to low-yielding environments (Fig 11 and 12). Of these, three hybrids (13,16 and 21) had mean yields below average for most of the yield range (above 8 t/ha) resulting in low mean yields across sites. Their yield performance in the low-yielding environments is inferior to that of the best

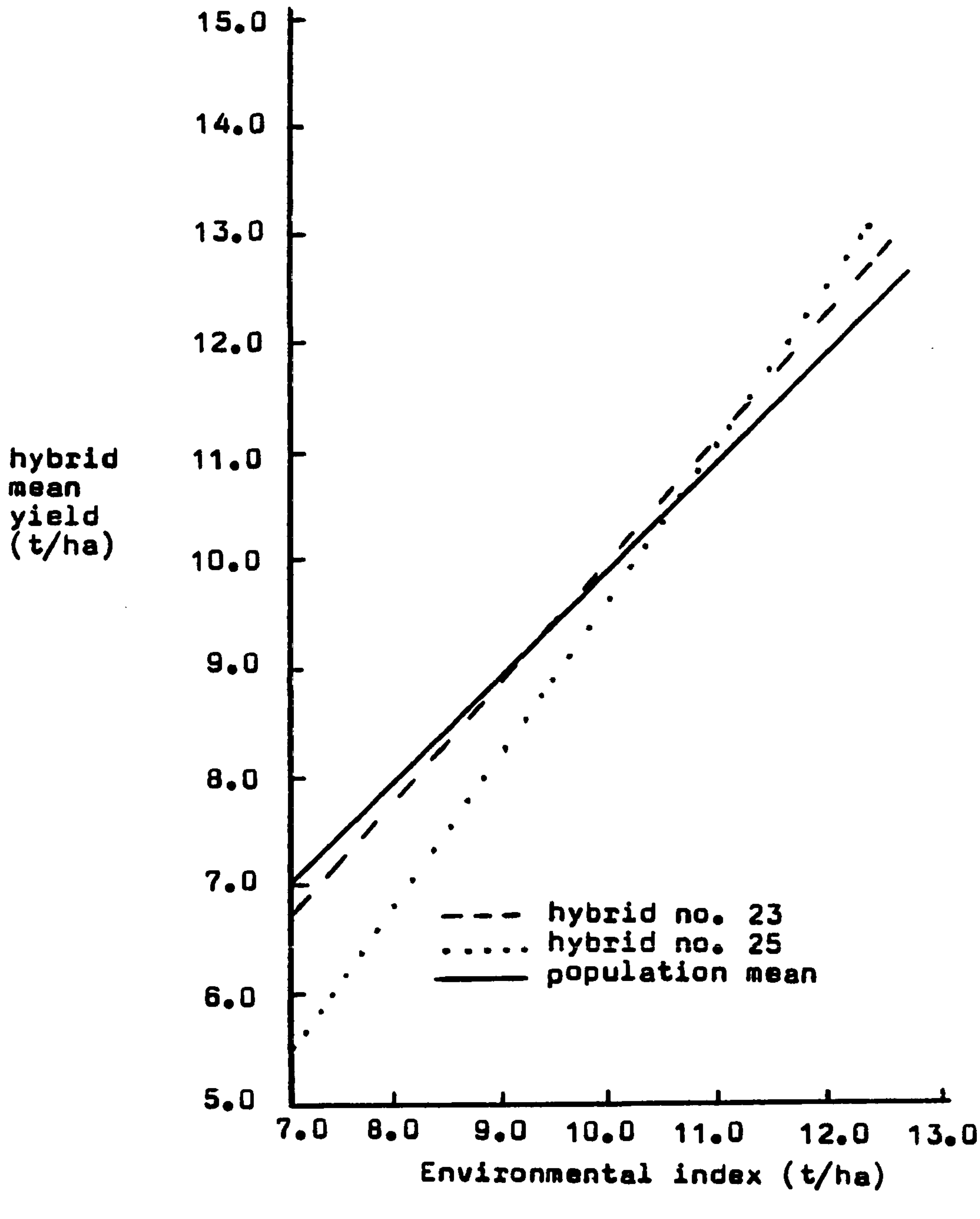


Fig 10. Yield responses of two maize hybrids adapted to high-yielding environments

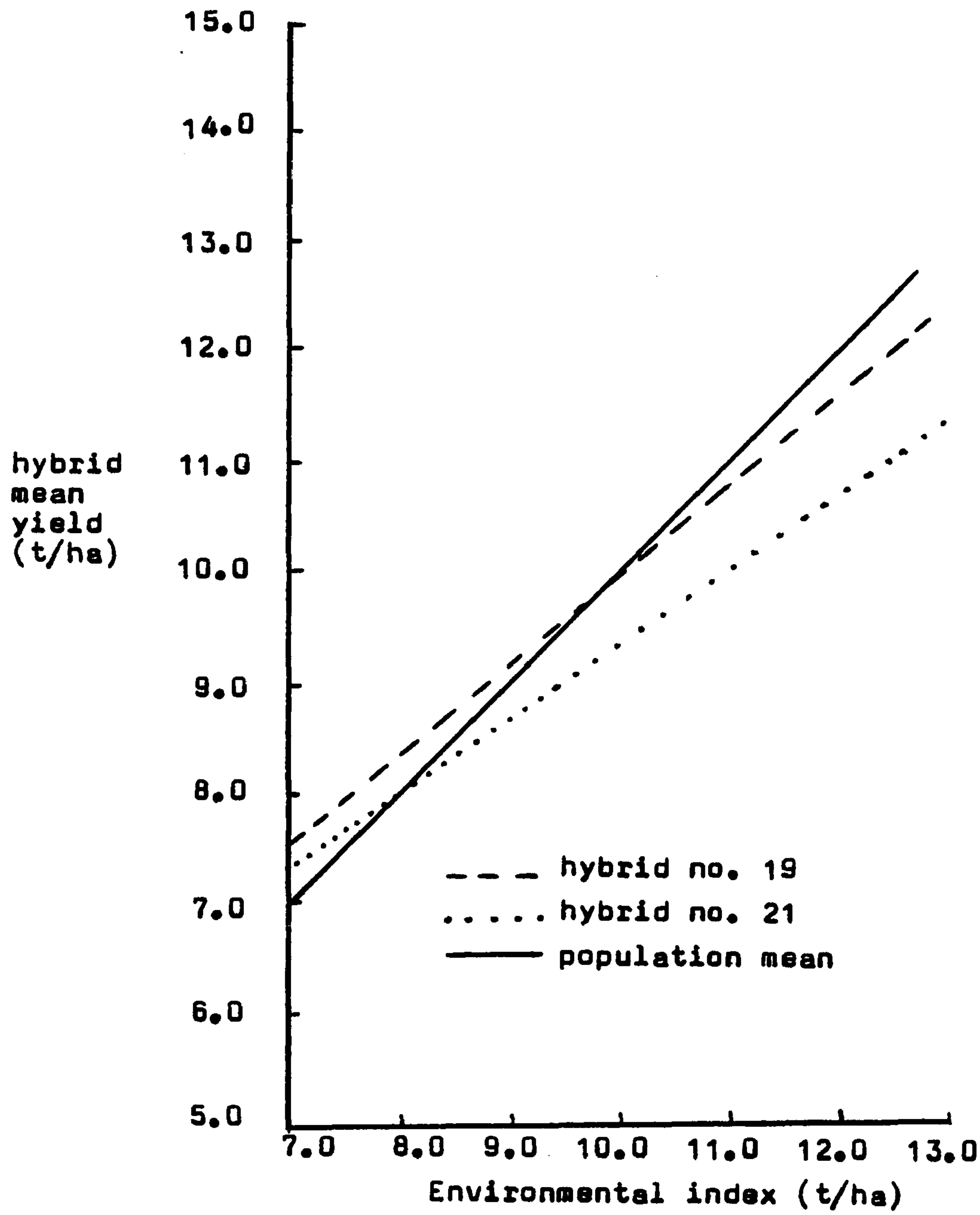


Fig 11. Yield responses of two maize hybrids adapted to low-yielding environments

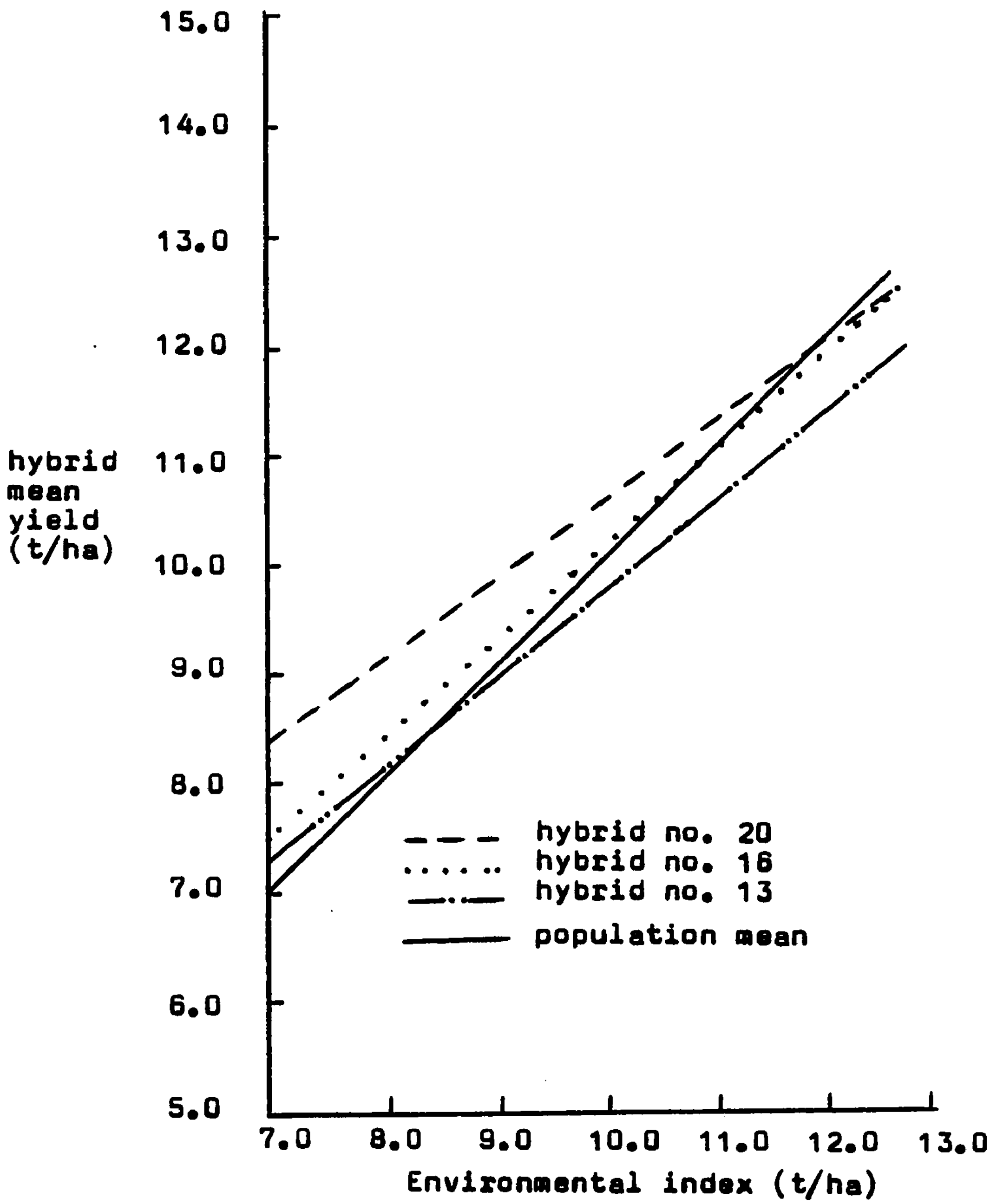


Fig 12. Yield responses of three maize hybrids adapted to low-yielding environments

well-adapted hybrids and hence seem to be undesirable even in the low-yielding environments. Hybrid 20 had mean yields above average throughout most of the yield range resulting in its above average mean yield across environments (Table 8). Its regression coefficient was significantly less than unity (b=0.75) indicating its inability to exploit highly favourable environments, beyond 12.0 t/ha. Hybrid 19 is well adapted to low-yielding environments below 10.0 t/ha but lacks the ability to exploit highly favourable environments (with b = 0.82) resulting in a lower than average mean yield across environments.

The results of this study show that the regression technique is a valuable tool for identifying varieties specifically adapted to specific types of environments and would be a valuable tool in making variety recommendations. Such varieties cannot be easily identified and could even be discarded if selection were on the basis of mean yield across sites. Selection for specific adaptation would be particularly important in breeding for stress resistance (e.g. drought resistance).To be useful for making selections b values should be used in conjunction with mean yields across environments. Graphing of the regression lines is particularly effective in emphasizing the trend of performance to a range of environments. Selection based on mean yield across sites is adequate for selecting widely adapted varieties but does not identify varieties with specific adaptation. The results also show that it is possible to develop high-yielding widely adapted varieties that are superior to specifically adapted varieties, in their areas of adaptation.

4.2. Stability

If the stability of a variety is assumed to be a measure of how well the observed response agrees with the expected response derived from the linear equation, then the parameter estimates (r^2, S_d^2 and σ_s^2) that measure the dispersion of points around the best fitting linear regression are the best measures of stability (Bilbro and Ray, 1976; Breese, 1969; Langer et al., 1979). High r^2 values and low values of S_d^2 and σ_s^2 indicate that the variety response is highly predictable when based on site mean yield and b values. An entry was considered stable if its deviation from regression mean square or stability variance was not significantly different from the pooled error mean square or if its r^2 value was close to unity. On the basis of the stability parameter estimates S_d^2 and σ_s^2 all hybrids used in this study were unstable. All had S_d^2 and σ_s^2 values significantly different from the pooled error mean square (Table 8). The S_d^2 and σ_s^2 values ranged from 0.11 and 0.20 to 1.20 and 1.23, respectively (Table 8). Significant deviation from regression mean squares indicate non-linear response, specific interactions with environments or lack of stability. The coefficient of determination (r^2) is a measure of goodness of fit of the linear response and is a measure of the reliability of the linear response. The r^2 values for some of the entries in this study were rather low. The r^2 values ranged from 0.59 (for hybrid 21) to 0.92 (for hybrid 25). The distribution of observed means were not close to the expected relative varietal responses (Figs 4 to 12), indicating a poor fit of the linear regression lines.

Varieties with the smallest values of mean varietal correlations ($\bar{r}$) also had the smallest values of r^2 and, consequently, had the largest values of S_d^2 and σ_s^2 (Table 8). Thus part of the instability was a result of failure to follow the general pattern of response closely. However, varieties with relatively high $\bar{r}$ and r^2 values (e.g. hybrids 3, 9, 10, 11, 17, 18 and 25) also had highly significant S_d^2 and σ_s^2 values suggesting that the highly significant S_d^2 and σ_s^2 values were not only a result of a poor fit of the linear regression and/or poor average correlations of individual entries with the others (failure to follow the dominant pattern) but also a result of lack of stability. All the hybrids used in this study were developed by private seed companies (in or outside Michigan), so the initial selection and evaluation of these hybrids were conducted in environments other than those in which the stability trials were conducted, possibly without direct selection for stability. Thus, it is not surprising that none of these hybrids were stable. However, other workers (Beaver and Johnson, 1981; Walker and Fehr, 1978; Weaver et al., 1983) reported that varieties often demonstrate undesirable stability parameter estimates even when tested in the area where they were initially developed. This emphasizes the relative nature of stability and/or the need to do direct selection for stability.

There was no association between maturity and stability. There was an equal distribution of early and late maturing hybrids with relatively higher and lower values of the stability parameter estimates. In sorghum, Saeed and Francis (1983) reported that late maturing varieties were more stable than early maturing varieties.

Eberhart and Russell (1966) proposed that an ideal variety would be one which has the highest yield over a wide range of environments, average response (b = 1.0) and a deviation mean square of zero. Such a variety was not found in this study. Hybrids 4, 10, 11, 14 and 15 were the most desirable and widely adapted. Despite their significantly high deviations from regression mean squares and stability variances, they had regression coefficients (b values) close to unity, significantly high mean yields across environments and their observed mean yields were superior at all yield levels, being consistently at or above the site mean yields throughout the whole range of environments used in this study. Hybrid number 7 would also be desirable though unstable and yielding below average at two of the 16 environments.

5. Conclusions

The results of this study lead to the following conclusions:

1. The combined analysis of variance showed that a major portion of the highly significant GE interaction was attributed to genotype x location interaction effects, suggesting the need to replicate more over locations than years, if the two years were representative of year-to-year variance in Michigan.

2.The use of the mean of all varieties as a (non-independent) measure of the environment does not satisfy the requirements of a regression analysis but it provides sufficiently reliable estimates of adaptation and stability parameters, particularly if the entries are highly correlated.

3. Mean yield, adaptation and stability parameter estimates were relatively independent of one another, thus;

(i) it appears possible to develop high yielding varieties with various combinations of b and S_d^2 or σ_s^2 values.

(ii) selection on the basis of yield alone will not enhance stability for yield. This might explain why none of the hybrids used in this study were stable.

(iii) selection for yield adaptation and stability should be done independently and simultaneously with selection for yield.

4. the parameter estimates r^2, S_d^2 and σ_s^2 are highly and significantly correlated indicating that any of them should be a satisfactory parameter for measuring stability. However, caution should be exercised in describing as unstable those genotypes with high values of S_d^2 and σ_s^2 or low values of r^2 if the varieties are not highly correlated and/or the correlations are heterogeneous.

5. It is possible to develop high yielding and widely adapted hybrids that are superior to those with specific adaptation.

6. Variety adaptation and stability should be considered in developing varieties and in making variety recommendations.

7. The regression coefficient in conjunction with mean yield across environments enables the development or identification of genotypes with wide or specific adaptation, information which can be very useful in breeding for stress resistance or in making variety recommendations.

8. The regression technique provides complete information on adaptation and stability and is, therefore, more informative than the single parameter method of Shukla (1972).

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APPENDIX

7. APPENDIX

Appendix Table 1. List of single-cross maize hybrids used for stability analysis

Hybrid number	Brand name and hybrid designation	Source
1	Callahan 754	Callahan Seeds, IN 46074
2	Cargill 842	Cargill Seeds, MN 55440
3	Cargill 859	Cargill Seeds, MN 55440
4	Dairyland 1107	Dairyland Seed Co., WI 53095
5	Dairyland 1001	Dairyland Seed Co., WI 53095
6	DeKalb-Pfizer DK484	DeKalb-Pfizer Genetics, IL
7	DeKalb-Pfizer DK524	DeKalb-Pfizer Genetics, IL
8	Funk G-4312	Funk Seeds International, IL
9	Funk G-4342	Funk Seeds International, IL
10	Garno S-100X	Garno Seed Co., MI 49268
11	Glenn & Garno GX1007	Garno Seed Co., MI 49268
12	Golden Harvest H-2480	Sommer Bros. Seed Co., IL
13	Great Lakes GL-540	Great Lakes Hybrids, Inc., MI
14	Great Lakes 5922	Great Lakes Hybrids, Inc., MI
15	King K5574	King Grain Ltd., Canada
16	MFI 1834	MFI Seeds, MI 49072
17	Northrup King PX9345	Northrup King Co., MN 55440
18	Payco SX620	Payco Seeds, Inc., MN 55325
19	Pioneer 3737	Pioneer Hi-Bred Int. IN 46072
20	Pioneer 3744	Pioneer Hi-Bred Int. IN 46072
21	Pioneer 3901	Pioneer Hi-Bred Int. IN 4607
22	Renk RK66	Renk Seed Co., WI 53590
23	Rupp XR1639	Rupp Seeds, Inc., OH 43567
24	Stauffer S5340	Stauffer Seeds, Inc., WI 53711
25	Stauffer S5650	Stauffer Seeds, Inc., Wi 53711

Appendix Table 2. Branch County site information

	1985	1986
Planted	April 29	May 8
Harvested	October 24	October 29
Soil type	Gilford sandy loam	Gilford sandy loam
Previous crop	maize	maize
Row spacing	75cm (30 inches)	75cm
Fertilizer rates	209-74-0	36-92-120
Soil test:pH	6.5	5.6
P	240 (very high)	350 (very high)
K	200 (medium)	211 (medium)

Farm cooperator: David Labar, Union City.

Appendix Table 3. Cass County (irrigated) site information

	1985	1986
Planted	April 29	May 2
Harvested	October 23	October 8
Soil type	Oshtemo sandy loam	Oshtemo sandy loam
Previous crop	maize	maize
Row spacing	75cm (30 inches)	75cm
Fertilizer rates	343-44-131	248-44-131
Irrigation	200mm (8 inches)	125mm (5 inches)
Soil test:pH	6.8	6.8
P	230 (very high)	264 (very high)
K	440 (very high)	392 (very high)

Farm cooperator: Dave Cripe, Cassopolis.

Appendix Table 4. Huron County site information

	1985	1986
Planted	May 2	May 1
Harvested	October 29	November 6
Soil type	Kilmanagh loam	Kilmanagh loam
Previous crop	maize	maize
Row spacing	75cm (30 inches)	75cm
Fertilizer rates	197-63-129	148-62-99
Soil test:pH	7.6	7.7
P	85 (high)	81 (high)
K	180 (medium)	160 (medium)

Farm cooperator: William McCrea, Bad Axe.

Appendix Table 5. Ingham County (M.S.U.) site information

	1985	1986
Planted	April 26	April 24
Harvested	October 17	October 11
Soil type	Capac loam	Capac loam
Previous crop	maize	maize
Row spacing	90cm (36 inches)	90cm
Fertilizer rates	165-50-50	165-50-50
Soil test:pH	6.1	5.9
P	155 (very high)	186 (very high)
K	235 (high)	215 (high)

Farm cooperator: M.S.U., East Lansing.

Appendix Table 6. Kalamazoo County site information

	1985	1986
Planted	April 30	May 3
Harvested	October 24	October 30
Soil type	Kalamazoo loam	Kalamazoo loam
Previous crop	maize	maize
Rows spacing	75cm (30 inches)	75cm
Fertilizer rates	125-48-24	112-48-24
Soil test:pH	5.9	5.7
P	162 (very high)	161 (very high)
K	364 (very high)	286 (high)

Farm cooperator: Richard van Vrancken, Climax.

Appendix Table 7. Monroe County site information

	1985	1986
Planted	May 5	May 5
Harvested	October 26	October 28
Soil type	Brookston loam	Brookston loam
Previous crop	wheat-clover sod	wheat
Row spacing	75cm (30 inches)	75cm
Fertilizer rates	220-72-240	170-68-90
Soil test:pH	6.3	6.8
P	218 (very high)	97 (high)
K	435 (very high)	128 (low)

Farm cooperator: Gerald Heath, Milan.

NB All fertilizer rates represent actual amounts of NPK applied in lbs/acre.

Appendix Table 8. Montcalm County (dryland) site information

	1985	1986
Planted	May 1	April 30
Harvested	October 30	November 3
Soil type	Montcalm-McBride sandy loam	
Previous crop	alfalfa	Sudan grass
Row spacing	75cm (30 inches)	75cm
Fertilizer rates	253-135-135	253-135-135
Soil test:pH	5.6	6.1
P	505 (very high)	576 (very high)
K	184 (medium)	337 (very high)

Farm cooperator: Montcalm Research Farm, Lakeview (Theron Comden).

Appendix Table 9. Montcalm County (irrigated) site information

	1985	1986
Planted	May 1	April 30
Harvested	October 30	November 3
Soil type	Montcalm-McBride sandy loam	
Previous crop	alfalfa	Sudan grass
Row spacing	75cm (30 inches)	75cm
Fertilizer rates	253-135-135	253-135-135
Irrigation	150mm (6 inches)	131.25mm (5.25 inches)
Soil test:pH	5.6	6.1
P	505 (very high)	576 (very high)
K	184 (medium)	337 (very high)

Farm cooperator: Montcalm Research Farm, Lakeview (Theron Comden).

Appendix Table 10. Table of means for 25 maize hybrids grown at Branch County during the 1985 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
4	13.25 a ‡	204.34 a ‡	2.32	1.61
10	12.88 ab	198.66 ab	1.68	0.53
14	12.71 abc	196.06 abc	1.14	0.00
23	12.65 abc	195.12 abc	0.84	2.08
11	12.61 abc	194.40 abc	3.12	1.53
7	12.56 abc	193.64 abc	1.30	0.00
3	12.39 abcd	191.04 abcd	4.26	0.50
15	12.25 bcd	188.97 bcd	3.67	1.54
24	12.15 bcd	187.40 bcd	3.51	1.04
6	11.82 cd	182.19 cd	1.44	1.52
25	11.63 d	179.26 d	3.06	0.51
22	10.74 e	165.67 e	1.24	0.00
16	10.68 e	164.62 e	2.45	1.10
13	10.48 ef	161.61 ef	3.18	0.00
20	10.36 efg	159.71 efg	0.85	0.00
1	10.18 efg	156.92 efg	2.18	2.62
17	10.16 efg	156.64 efg	1.06	0.00
19	10.16 efg	156.63 efg	1.33	3.77
12	10.02 efg	154.52 efg	1.28	0.00
9	9.89 efg	152.57 efg	3.67	1.06
2	9.87 efg	152.14 efg	2.68	2.10
21	9.81 efg	151.21 efg	3.98	1.09
18	9.60 fg	147.96 fg	1.76	0.53
5	9.50 fg	146.51 fg	4.39	1.51
8	9.38 g	144.59 g	3.67	1.16
site mean	11.11	171.29	2.40	1.03
CV(%)	3.76	3.76	107.86	165.17
LSD(0.05)	0.59	9.12	3.67	2.41
LSD(0.01)	0.79	12.14	4.89	3.21
F-test	**	**	ns	ns
RE(%)	104	104	113	----

** F-test significant at the 0.01 probability level, and ns = F-test not significant at the 0.05 probability level; RE(%) = relative efficiency of the Simple Lattice Design over the Randomized Block Design, (---- = no efficiency).

‡ means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 11. Table of means for 25 maize hybrids grown at Branch County during the 1986 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
14	13.33 a‡	205.51 a‡	4.47	0.00
11	13.20 a	203.62 a	3.50	0.00
10	12.84 ab	197.98 ab	3.06	0.00
4	12.65 abc	195.09 abc	3.38	0.00
15	12.39 abc	190.99 abc	6.38	0.00
23	12.37 abc	190.76 abc	5.38	0.00
7	12.10 bcd	186.58 bcd	5.79	0.00
12	11.71 cde	180.53 cde	5.13	0.00
20	11.34 def	174.92 def	2.94	0.00
1	11.04 efg	170.30 efg	5.67	0.00
22	10.97 efgh	169.15 efgh	4.96	0.00
6	10.93 efgh	168.49 efgh	8.24	0.00
2	10.72 efgh	165.38 efgh	7.42	0.00
24	10.66 efgh	164.46 efgh	3.16	0.00
19	10.58 fgh	163.10 fgh	7.13	0.00
3	10.41 fghi	160.52 fghi	7.18	0.00
9	10.25 fghi	158.07 fghi	9.06	0.00
25	10.07 ghi	155.35 ghi	7.42	0.00
13	9.99 ghij	154.04 ghij	9.12	0.00
17	9.96 ghij	153.66 ghij	1.98	0.00
16	9.81 hij	151.31 hij	2.76	0.00
8	9.44 ij	145.51 ij	7.14	0.00
5	9.38 ij	144.72 ij	13.60	0.00
21	9.36 ij	144.35 ij	6.53	0.00
18	8.96 j	138.10 j	7.82	0.00
site mean	10.98	169.30	5.97	0.00
CV(%)	4.50	4.50	55.16	----
LSD(0.05)	0.70	10.78	4.66	----
LSD(0.01)	0.93	14.35	6.21	----
F-test	**	**	**	----
RE(%)	----	110	----	----

** F-test significant at the 0.01 probability level;

RE(%) = relative efficiency of the Simple Lattice Design over the Randomized Block Design, (---- = no efficiency)

‡ means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 12. Table of means for 25 maize hybrids grown at Cass County (irrigated trial) during the 1985 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
8	13.89 a +	206.44 a+	3.45	3.35
4	13.33 ab	205.53 ab	1.00	2.06
14	13.17 ab	203.11 ab	1.16	0.00
1	13.13 ab	202.44 ab	1.11	1.67
10	12.93 abc	199.43 abc	3.22	2.11
7	12.90 abc	198.85 abc	1.14	0.00
24	12.83 abc	197.88 abc	3.87	0.52
11	12.74 abc	196.43 abc	2.14	1.10
15	12.63 bc	194.75 bc	2.87	1.63
23	12.38 cd	190.84 cd	1.61	1.09
19	12.07 de	186.14 de	3.29	3.70
3	11.98 de	184.78 de	2.06	3.17
2	11.69 ef	180.24 ef	2.57	2.09
20	11.65 ef	179.68 ef	3.22	0.00
9	11.63 ef	179.29 e	3.67	1.25
6	11.58 ef	178.62 ef	7.52	3.22
25	11.57 ef	178.37 ef	0.52	0.00
13	11.40 ef	175.86 ef	5.76	0.00
16	11.02 fg	169.99 fg	1.60	2.10
12	10.83 gh	167.07 gh	1.71	0.00
17	10.42 hi	160.75 hi	3.08	0.00
5	10.26 i	158.22 i	9.27	4.40
22	10.20 i	157.30 i	1.66	0.00
18	10.12 i	156.11 i	3.27	6.75
21	9.65 j	148.85 j	1.16	1.06
site mean	11.82	182.28	2.88	1.65
CV(%)	2.69	2.69	104.27	189.58
LSD(0.05)	0.45	6.93	4.25	4.43
LSD(0.01)	0.60	9.23	5.65	5.90
F-test	**	**	*	ns
RE(%)	102	102	----	----

*,** F-test significant at the 0.05 and 0.01 probability level, respectively, and ns = F-test not significant at the 0.05 probability level;

RE(%) = relative efficiency of the Simple Lattice Design over the Randomized Block Design, (---- = no efficiency).
+means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 13. Table of means for 25 maize hybrids grown at Cass County (irrigated trial) during the 1986 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
14	13.24 a ‡	204.21 a ‡	2.89	2.51
4	12.67 ab	195.33 ab	3.80	2.62
11	12.65 ab	195.09 ab	1.88	2.50
15	12.62 ab	194.59 ab	5.84	2.50
7	12.01 bc	185.25 bc	1.16	2.08
1	11.91 bc	183.66 bc	1.64	4.83
10	11.70 c	180.36 c	3.90	2.00
3	11.51 cd	177.53 cd	4.21	0.53
6	11.38 cde	175.41 cde	1.03	1.70
23	11.28 cde	173.94 cde	3.48	3.62
9	11.21 cdef	172.93 cdef	8.66	1.50
16	11.04 cdef	170.25 cdef	1.37	2.00
20	11.04 cdef	170.23 cdef	0.39	1.09
13	11.01 cdef	169.71 cdef	1.51	0.50
24	10.67 defg	164.51 defg	1.91	1.75
25	10.65 defg	164.30 defg	4.45	3.26
8	10.56 defg	162.88 defg	3.21	1.60
22	10.55 defg	162.66 defg	3.34	2.02
19	10.45 efg	161.14 efg	0.78	1.50
2	10.42 efg	160.70 efg	2.95	0.53
12	10.19 fg	157.11 fg	3.45	2.01
17	9.99 g	154.10 g	1.77	1.50
18	9.70 g	149.59 g	3.51	7.50
5	9.70 g	149.54 g	3.48	1.00
21	9.62 g	148.42 g	1.79	0.00
site mean	11.11	171.34	2.90	2.11
CV(%)	3.93	3.93	106.37	128.43
LSD(0.05)	0.62	9.50	4.37	3.83
LSD(0.01)	0.82	12.64	5.81	5.10
F-test	**	**	ns	ns
RE(%)	----	----	102	----

** F-test significant at the 0.01 probability level, and ns = F-test not significant at the 0.05 probability level;

RE(%) = relative efficiency of the Simple Lattice Design over the Randomized Block Design, (---- = no efficiency).

‡means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 14. Table of means for 25 maize hybrids grown at Huron County during the 1985 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
7	10.98 a‡	169.31 a‡	0.00	0.00
8	10.98 a	169.26 a	1.68	0.00
14	10.97 a	169.10 a	1.05	0.52
20	10.77 ab	166.02 ab	0.51	1.02
5	10.71 abc	165.22 abc	1.61	2.11
17	10.54 abc	162.49 abc	1.16	0.51
19	10.49 abc	161.71 abc	1.52	1.56
11	10.46 abc	161.34 abc	1.62	0.54
15	10.36 abc	159.70 abc	1.54	1.55
10	10.16 abcd	156.68 abcd	0.00	1.04
3	10.16 abcd	156.62 abcd	1.59	3.76
21	10.02 abcde	154.56 abcde	1.05	6.20
1	9.96 abcde	153.64 abcde	2.13	0.00
4	9.94 abcde	153.21 abcde	0.00	0.52
16	9.93 abcde	153.19 abcde	0.00	2.06
6	9.89 abcde	152.45 abcde	0.52	1.06
13	9.70 abcde	149.61 abcde	2.18	1.67
23	9.67 abcde	149.07 abcde	1.74	0.50
9	9.49 bcdef	146.27 bcdef	2.83	4.26
2	9.38 cdef	144.59 cdef	0.00	3.02
18	9.04 def	139.35 def	3.33	0.60
12	8.79 ef	135.60 ef	2.15	0.00
24	8.78 ef	135.33 ef	0.00	1.02
25	8.48 f	130.82 f	0.57	0.00
22	8.42 f	129.92 f	2.13	3.80
site mean	9.92	153.00	1.24	1.49
CV(%)	5.30	5.30	143.04	175.52
LSD(0.05)	0.74	11.48	2.51	3.71
LSD(0.01)	0.99	15.28	3.33	4.94
F - test	**	**	ns	ns
RE(%)	101	101	----	----

**F-test significant at the 0.01 probability level;
ns = F-test not significant at the 0.05 probability level;

RE(%) = relative efficiency of the Simple Lattice design over a Randomized Block Design, (---- represents no efficiency).

‡means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 15. Table of means for 25 maize hybrids grown at Huron County during the 1986 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
14	9.64 a‡	148.72 a‡	0.00	1.17
24	8.80 b	135.73 b	0.51	0.50
20	8.78 b	135.45 b	3.64	0.14
2	8.75 b	134.92 b	1.04	0.38
7	8.66 b	133.58 b	5.58	3.36
19	8.62 b	132.89 b	2.86	0.58
13	8.49 b	130.94 b	2.55	0.69
4	8.45 b	130.26 b	0.52	4.73
15	8.37 bc	129.13 bc	3.08	5.97
11	8.35 bc	128.79 bc	0.50	4.08
16	8.31 bc	128.17 bc	0.53	1.53
10	7.99 cd	123.28 cd	1.02	4.17
25	7.80 de	120.27 de	1.52	0.09
6	7.80 de	120.23 de	4.58	9.04
21	7.66 de	118.13 de	2.56	1.88
12	7.65 de	117.95 de	3.66	6.93
3	7.50 ef	115.71 ef	4.13	13.33
23	7.50 ef	115.68 ef	2.59	6.31
17	7.39 ef	114.00 ef	4.13	0.40
1	7.19 f	110.85 f	2.08	0.00
5	6.66 g	102.67 g	3.09	0.10
8	6.65 g	102.58 g	4.58	2.18
18	6.51 g	100.37 g	1.75	2.20
9	6.42 g	98.99 g	4.60	1.00
22	5.82 h	89.75 h	3.61	1.84
site mean	7.83	120.76	2.59	2.90
CV(%)	2.74	2.74	95.47	123.98
LSD(0.05)	0.30	4.69	3.50	5.09
LSD(0.01)	0.40	6.24	4.66	6.78
F -test	**	**	*	**
RE(%)	103	103	----	101

*,** F-test significant at the 0.05 and 0.01 probability levels, respectively;

RE(%) = relative efficiency of the Simple Lattice design over the Randomized Block Design, (---- = no efficiency).

‡means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 16. Table of means for 25 maize hybrids grown at Ingham County (M.S.U. field plots) during the 1985 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)	ear height (cm)	plant ht (cm)
15	11.43 a‡	176.18 a‡	0.00	0.63	101.8	232.1
6	11.42 a	176.10 a	0.00	1.58	87.2	220.3
4	11.22 ab	173.05 ab	0.00	3.37	103.1	224.8
1	11.17 ab	172.25 ab	0.00	1.56	99.4	221.6
14	11.06 abc	170.58 abc	0.00	0.58	88.3	235.9
24	11.06 abc	170.57 abc	0.00	2.19	99.8	227.1
10	10.92 abcd	168.38 abcd	0.00	2.72	107.1	235.0
11	10.81 abcde	166.64abcde	0.00	3.10	99.9	234.2
16	10.80 abcde	166.54abcde	0.00	2.02	99.4	221.4
7	10.69 bcde	164.91 bcde	0.56	0.51	102.0	245.5
2	10.62 bcde	163.78 bcde	0.00	0.00	98.2	229.9
23	10.48 cdef	161.67 cdef	0.00	1.12	105.0	230.3
20	10.40 cdef	160.40 cdef	0.00	0.53	77.9	220.8
13	10.40 cdef	160.30 cdef	0.00	0.00	74.6	227.7
8	10.27 def	158.34 def	0.00	2.15	84.5	232.2
3	10.22 ef	157.55 ef	0.00	4.56	78.2	210.5
5	10.18 ef	156.96 ef	0.00	1.58	61.3	200.7
17	9.94 fg	153.23 fg	0.00	2.13	86.3	222.4
9	9.61 gh	148.19 gh	0.00	1.16	86.6	221.7
22	9.60 gh	148.10 gh	0.58	0.00	90.8	235.9
19	9.54 gh	147.05 gh	0.00	1.85	77.4	221.0
21	9.23 hi	142.28 hi	0.00	1.04	85.7	220.6
25	9.05 hi	139.52 hi	0.00	1.21	103.7	242.3
18	8.92 i	137.54 i	0.00	1.22	82.5	218.1
12	8.90 i	137.31 i	0.00	0.56	88.5	243.5
site mean	10.32	159.10	0.05	1.49	90.8	227.0
CV(%)	2.81	2.81	765.85	120.89	3.1	3.1
LSD(.05)	0.41	6.33	0.49	5.09	4.7	11.8
LSD(.01)	0.55	8.42	0.66	6.78	6.3	15.8
F-test	**	**	ns	ns	**	**
RE(%)	125	125	----	----	365	231

** F-test significant at the 0.01 probability level, and ns = F-test not significant at the 0.05 probability level;

RE(%) = the relative efficiency of the Simple Lattice Design over the Randomized Block Design, (---- = no efficiency).

‡ means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 17. Table of means for 25 maize hybrids grown at Ingham County (M.S.U. field plots) during the 1986 summer season

hybrid number	grain yield (t/ha)		grain yield (bu/acre)	stalk lodging (%)	root lodging (%)	ear ht (cm)	plant ht (cm)	of cobs per 100 plants
14	12.06	a‡	185.99	14.35	0.00	91.3	245.2	98.9
15	11.39	b	175.59	9.68	0.00	102.2	248.0	111.9
10	11.37	b	175.30	15.60	0.00	99.2	238.5	106.2
11	11.22	b	173.00	22.86	0.00	100.8	237.8	108.9
24	10.90	c	168.04	10.15	3.18	103.3	236.8	113.2
4	10.74	cd	165.58	9.82	4.23	103.7	239.7	108.4
6	10.59	cd	163.36	14.95	0.00	81.0	222.0	105.2
1	10.59	cd	163.32	14.12	5.05	106.3	240.8	113.4
20	10.47	cd	161.44	5.45	0.00	75.4	233.7	103.7
3	10.35	de	159.54	10.05	0.50	87.9	226.8	105.7
16	10.08	ef	155.38	11.58	0.52	96.8	242.9	111.2
7	10.00	ef	154.13	8.06	0.00	92.5	240.8	102.1
8	9.90	f	152.69	11.60	0.00	73.4	238.4	98.9
23	9.83	fg	151.58	11.47	3.00	99.5	236.1	108.3
2	9.67	fg	149.12	6.23	2.66	103.7	246.4	100.9
19	9.63	fgh	148.51	4.64	0.00	77.2	232.6	107.8
9	9.41	gh	145.17	9.15	0.00	82.6	230.5	98.8
22	9.41	gh	145.13	11.37	0.52	101.7	248.6	97.4
17	9.40	gh	145.02	3.28	0.00	84.6	237.9	105.7
13	9.19	hi	141.65	5.57	0.00	70.6	230.0	101.7
21	8.89	ij	137.03	10.52	0.00	82.0	226.2	99.0
25	8.74	j	134.77	9.48	0.00	99.2	247.7	97.2
12	8.37	k	129.06	16.31	1.00	94.4	253.5	99.7
5	8.35	k	128.70	6.14	0.00	60.5	215.8	108.2
18	8.27	k	127.50	10.18	1.02	83.7	231.2	99.0
site mean	9.95		153.46	10.50	0.87	90.1	237.1	104.5
CV(%)	2.27		2.27	53.48	287.55	5.7	2.9	5.2
LSD(.05)	0.32		4.94	7.96	3.53	7.2	9.8	7.7
LSD(.01)	0.43		6.58	10.59	4.7	9.6	13.1	10.2
F-test	**		**	**	ns	**	**	**
RE(%)	108		108	105	----	102	108	----

** F-test significant at the 0.01 probability level, and ns = F-test not significant at the 0.05 probability level;

RE(%) = relative efficiency of the Simple Lattice Design over the Randomized Block Design, (---- = no efficiency).

‡ means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 18. Table of means for 25 maize hybrids grown at Kalamazoo County during the 1985 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
14	8.47 a‡	130.57 a‡	1.10	0.03
20	8.35 ab	128.80 ab	0.54	1.06
4	8.35 ab	128.79 ab	2.22	0.68
10	8.27 ab	127.57 ab	2.10	0.53
15	8.23 ab	126.89 ab	1.62	0.06
11	8.02 abc	123.64 abc	2.21	0.00
1	7.96 abc	122.72 abc	1.56	0.97
19	7.66 abcd	118.09 abcd	2.55	0.00
21	7.49 bcd	115.50 bcd	1.67	4.03
7	7.44 bcd	114.67 bcd	1.58	0.03
3	7.21 cd	111.21 cd	4.81	1.32
16	7.16 cd	110.44 cd	1.00	0.22
18	7.04 d	108.57 d	2.69	2.09
6	6.99 d	107.86 d	0.50	1.33
8	6.98 d	107.61 d	1.06	1.61
13	6.93 d	106.86 d	1.15	0.11
23	6.79 de	104.71 de	0.00	0.64
22	6.12 ef	94.40 f	1.64	0.00
24	6.10 ef	94.04 ef	4.22	0.55
9	6.06 ef	93.38 ef	1.62	1.63
17	6.00 ef	92.56 ef	1.14	0.43
2	5.94 ef	91.55 ef	1.56	0.71
5	5.80 f	89.48 f	2.03	0.72
12	5.58 f	86.04 f	1.14	0.00
25	5.54 f	85.48 f	1.04	0.06
site mean	7.06	108.86	1.71	0.74
CV(%)	6.03	6.03	109.74	221.15
LSD(0.05)	0.60	9.30	2.66	2.31
LSD(0.01)	0.80	12.38	3.54	3.08
F - test	**	**	ns	ns
RE(%)	----	----	----	106

** F - test significant at the 0.01 probability leve, and ns = F - test not significant at the 0.05 probability level;

RE(%) = relative efficiency of the Simple Lattice design over the Randomized Block Design, (---- = no efficiency).

‡ means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 19. Table of means for 25 maize hybrids grown at Kalamazoo County during the 1986 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
11	11.02 a‡	169.90 a‡	2.00	0.00
14	10.89 a	167.93 a	1.06	0.00
3	10.51 ab	162.07 ab	1.54	0.00
20	10.47 ab	161.52 ab	1.56	0.00
7	10.40 abc	160.40 abc	3.52	0.00
10	10.40 abc	160.38 abc	3.56	0.00
8	10.40 abc	160.37 abc	2.04	0.00
2	10.29 abc	158.69 abc	5.19	0.00
1	10.06 abcd	155.08 abcd	4.73	0.00
4	9.60 bcde	148.03 bcde	5.29	0.00
24	9.55 bcde	147.23 bcde	2.62	0.00
19	9.50 bcde	146.52 bcde	2.13	0.00
15	9.50 bcde	146.49 bcde	4.06	0.00
6	9.46 bcde	145.88 bcde	2.04	0.00
12	9.43 bcde	145.34 bcde	6.65	0.00
23	9.36 cde	144.35 cde	3.56	0.00
13	9.11 def	140.40 def	3.13	0.00
16	9.04 def	139.33 def	1.71	0.00
9	8.75 ef	134.94 ef	3.00	0.00
22	8.67 ef	133.64 ef	0.00	0.00
21	8.62 ef	132.94 ef	2.54	0.00
25	8.57 ef	132.13 ef	2.74	0.00
5	8.35 f	128.76 f	4.69	0.00
17	8.29 f	127.80 f	0.51	0.00
18	8.22 f	126.80 f	3.56	0.00
site mean	9.54	147.08	2.94	0.00
CV(%)	4.63	4.63	88.40	----
LSD(0.05)	0.63	9.64	3.64	----
LSD(0.01)	0.83	12.83	4.85	----
F - test	**	**	ns	----
RE(%)	109	109	----	----

** F-test significant at the 0.01 probability level, and ns = F-test not significant at the 0.05 probability level;

RE(%) = relative efficiency of the Simple Lattice design over the Randomized Block Design, (---- = no efficiency).

‡ means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 20. Table of means for 25 maize hybrids grown at Monroe County during the 1985 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
14	12.94 a ‡	199.51 a ‡	3.44	1.53
15	12.82 ab	197.69 ab	1.83	5.23
3	12.70 ab	195.78 ab	8.27	1.03
4	12.65 ab	195.11 ab	3.00	4.26
8	12.54 ab	193.34 ab	3.88	2.14
7	12.44 b	191.78 b	1.64	0.00
11	12.42 b	191.46 b	2.27	5.24
10	12.41 b	191.34 b	1.63	2.05
6	11.98 c	184.78 c	3.22	0.53
9	11.57 d	178.45 d	2.28	0.51
1	11.53 d	177.82 d	1.80	4.61
24	11.42 d	176.11 d	5.03	1.60
2	11.07 e	170.75 e	4.81	5.19
25	10.93 ef	168.53 ef	1.30	1.71
20	10.75 efg	165.74 efg	3.06	0.63
13	10.72 efg	165.36 efg	5.27	1.76
19	10.70 efg	164.93 efg	5.09	2.67
5	10.55 fg	162.68 fg	7.81	1.51
16	10.48 fg	161.55 fg	3.36	1.62
17	10.31 gh	158.98 gh	1.18	1.06
23	10.29 gh	158.70 gh	0.15	2.07
12	9.97 hi	153.76 hi	3.43	1.09
18	9.74 i	150.17 i	2.92	1.74
21	9.64 i	148.69 i	6.13	2.00
22	9.23 j	142.32 j	7.56	4.56
site mean	11.27	173.81	3.61	2.25
CV(%)	2.11	2.11	110.13	131.67
LSD(0.05)	0.34	5.18	5.64	4.20
LSD(0.01)	0.45	6.90	7.51	5.59
F-test	**	**	ns	ns
RE(%)	----	----	101	----

** F-test significant at the 0.01 probability level, and ns = F-test not significant at the 0.05 probability level;

RE(%) = relative efficiency of the Simple Lattice Design over the Randomized Block Design, (---- = no efficiency).

‡means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 21. Table of means for 25 maize hybrids grown at Monroe County during the 1986 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
14	12.87 a‡	198.49 a‡	3.00	0.00
15	12.76 a	196.75 a	9.12	0.00
11	12.20 ab	188.07 ab	5.67	0.00
7	12.18 ab	187.83 ab	6.54	0.00
8	11.66 bc	179.80 bc	6.52	0.00
4	11.61 bc	179.07 bc	6.24	0.00
10	11.33 bcd	174.76 bcd	6.53	0.00
20	11.28 bcd	173.89 bcd	5.27	0.00
6	11.19 bcd	172.57 bcd	8.64	0.00
19	11.11 bcde	171.35 bcde	8.22	0.00
9	11.10 bcde	171.11 bcde	6.83	0.00
23	10.96 cdef	169.06 cdef	6.62	0.00
24	10.82 cdef	166.91 cdef	6.45	0.00
3	10.76 cdef	165.87 cdef	4.67	0.00
25	10.21 defg	157.42 defg	6.05	0.00
13	10.18 defg	157.03 defg	5.52	0.00
12	10.16 defg	156.66 defg	6.82	0.00
17	9.94 efg	153.35 efg	3.68	0.00
5	9.93 efg	153.20 efg	9.87	0.00
22	9.91 efg	152.75 efg	5.30	0.00
16	9.86 fg	152.07 fg	3.09	0.00
2	9.83 fg	151.57 fg	5.26	0.00
1	9.81 fg	151.24 fg	5.10	0.00
21	9.73 fg	150.06 fg	5.31	0.00
18	9.45 g	145.72 g	11.51	0.00
site mean	10.83	167.06	6.31	0.00
CV(%)	5.02	5.02	77.65	----
LSD(0.05)	0.77	11.87	6.94	----
LSD(0.01)	1.02	15.81	9.24	----
F-test	**	**	ns	----
RE(%)	----	----	114	----

** F-test significant at the 0.01 probability level, and ns = F-test not significant at the 0.05 probability level;

RE(%) = relative efficiency of the Simple Lattice Design over the Randomized Block Design, (---- = no efficiency).

‡means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 22. Table of means for 25 maize hybrids grown at Montcalm County (dryland trial) during the 1985 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
14	11.95 a ‡	184.32 a ‡	0.00	0.00
3	11.52 ab	177.65 ab	0.00	0.00
21	11.46 abc	176.68 abc	1.03	0.00
8	11.39 abc	175.65 abc	0.00	0.00
6	11.37 abc	175.33 abc	0.53	0.00
13	11.31 bcd	174.38 bcd	0.00	0.00
15	11.08 bcde	170.89 bcde	0.00	0.00
4	11.06 bcde	170.49 bcde	0.00	0.00
20	10.97 bcde	169.17 bcde	0.52	0.00
2	10.94 bcdef	168.73 bcdef	1.04	0.00
24	10.80 cdefg	166.48 cdefg	0.51	0.54
10	10.79 cdefg	166.40 cdefg	0.00	0.00
11	10.67 defg	164.58 defg	0.57	0.52
5	10.54 efgh	162.45 efgh	0.63	0.53
12	10.49 efgh	161.70 efgh	0.00	0.53
23	10.39 efgh	160.13 efgh	0.00	0.00
7	10.29 fgh	158.66 fgh	0.00	0.00
9	10.21 ghi	157.46 ghi	0.00	0.00
16	10.01 hi	154.32 hi	1.09	0.54
1	9.97 hi	153.70 hi	0.00	0.00
25	9.92 hi	152.96 hi	0.56	0.00
18	9.66 ij	148.94 ij	1.10	0.00
17	9.40 j	144.88 j	0.00	0.00
19	9.22 j	142.10 j	0.51	0.54
22	9.17 j	141.41 j	0.00	0.00
site mean	10.58	163.18	0.32	0.13
CV(%)	2.86	2.86	282.69	421.81
LSD(0.05)	0.43	6.61	1.29	0.77
LSD(0.01)	0.57	8.80	1.72	1.02
F-test	**	**	ns	ns
RE(%)	----	----	----	----

** F-test significant at the 0.01 probability level, and ns = F-test not significant at the 0.05 probability level;

RE(%) = relative efficiency of the Simple Lattice Design over the Randomized Block Design, (---- = no efficiency).

‡means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 23. Table of means for 25 maize hybrids grown at Montcalm County (dryland trial) during the 1986 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
14	12.32 a‡	190.04 a‡	3.26	0.00
11	11.85 b	182.73 b	4.23	0.00
20	11.19 c	172.61 c	4.56	0.00
24	11.13 c	171.67 c	7.03	0.00
19	11.05 cd	170.32 cd	2.86	0.00
15	10.95 cde	168.89 cde	2.47	0.00
7	10.84 cdef	167.11 cdef	5.76	0.00
10	10.75 cdefg	165.83 cdefg	4.82	0.00
13	10.64 defg	164.01 defg	3.69	0.50
12	10.54 efgh	162.50 efgh	4.36	0.00
3	10.38 fghi	160.05 fghi	4.48	0.00
21	10.29 ghi	158.67 ghi	5.00	0.00
4	10.12 hij	156.02 hij	8.53	0.00
6	10.07 hij	155.30 hij	8.09	0.00
23	9.94 ijk	153.29 ijk	3.46	0.50
25	9.73 jk	150.06 jk	2.78	1.50
17	9.59 k	147.82 k	5.45	0.00
22	9.56 k	147.42 k	4.20	3.00
2	9.51 k	146.61 k	5.63	0.00
8	8.83 l	136.09 l	8.77	0.00
9	9.77 l	135.24 l	8.66	0.00
18	8.67 lm	133.62 lm	7.89	1.00
16	8.66 lm	133.61 lm	7.33	0.00
1	8.66 lm	133.61 lm	7.00	0.00
5	8.27 m	127.53 m	2.74	0.50
site mean	10.09	155.62	5.32	0.28
CV(%)	2.31	2.31	59.29	342.09
LSD(0.05)	0.33	5.09	4.47	1.34
LSD(0.01)	0.44	6.77	5.95	1.78
F-test	**	**	ns	**
RE(%)	101	101	110	----

** F-test significant at the 0.01 probability level, and ns = F-test not significant at the 0.05 probability level;

RE(%) = relative efficiency of the Simple Lattice Design over the Randomized Block Design, (---- = no efficiency).

‡ means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 24. Table of means for 25 maize hybrids grown at Montcalm County (irrigated trial) during the 1985 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
25	13.52 a‡	208.55 a‡	0.56	0.00
16	13.35 ab	205.90 ab	0.54	0.00
12	13.18 abc	203.19 abc	0.54	0.00
1	13.03 bcd	200.88 bcd	0.52	0.99
15	13.01 bcd	200.56 bcd	0.00	0.00
11	12.91 bcd	199.13 bcd	1.09	0.00
10	12.89 bcd	198.73 bcd	0.54	0.21
9	12.76 cd	196.69 cd	1.60	0.26
22	12.73 cd	196.31 cd	0.53	0.00
4	12.72 cd	196.19 cd	0.00	0.80
14	12.55 de	193.49 de	0.00	0.05
24	12.50 def	192.68 def	0.00	0.59
23	12.46 def	192.08 def	1.14	0.44
13	12.19 efg	188.02 efg	1.11	0.00
3	12.06 fgh	186.01 fgh	1.09	0.14
2	11.89 gh	183.34 gh	0.53	0.68
17	11.86 gh	182.88 gh	1.16	0.00
7	11.78 gh	181.68 gh	0.00	0.16
20	11.74 gh	181.02 gh	1.14	0.00
19	11.57 hi	178.47 hi	0.56	0.56
8	11.56 hi	178.32 hi	0.00	1.32
18	11.16 ij	172.03 ij	0.60	0.00
6	10.97 j	169.14 j	1.11	1.10
5	10.91 j	168.29 j	0.00	0.19
21	10.18 k	157.02 k	0.51	0.21
site mean	12.22	188.42	0.59	0.27
CV(%)	1.98	1.98	221.44	315.39
LSD(0.05)	0.34	5.29	1.85	1.19
LSD(0.01)	0.46	7.04	2.46	1.58
F-test	**	**	ns	ns
RE(%)	101	101	----	128

** F-test significant at the 0.01 probability level, and ns = F-test not significant at the 0.05 probability level;

RE(%) = relative efficiency of the Simple Lattice Design over the Randomized Block Design, (---- = no efficiency.

‡means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.

Appendix Table 25. Table of means for 25 maize hybrids grown at Montcalm County (irrigated trial) during the 1986 summer season

hybrid number	grain yield (t/ha)	grain yield (bu/acre)	stalk lodging (%)	root lodging (%)
14	14.76 a‡	227.62 a‡	1.03	2.74
11	14.14 b	218.09 b	1.50	5.78
25	13.93 b	214.82 b	0.54	4.80
3	13.82 bc	213.12 bc	2.00	4.79
20	13.81 bc	213.02 bc	1.00	0.79
13	13.32 cd	205.38 cd	1.00	0.18
7	13.32 cd	205.37 cd	1.00	1.75
19	13.24 cd	204.22 cd	2.00	0.11
6	13.12 d	202.26 d	1.50	0.00
10	13.00 d	200.45 d	3.50	3.65
2	12.94 de	199.61 de	2.50	1.50
4	12.92 de	199.30 de	1.50	6.73
21	12.92 de	199.29 de	2.00	0.00
15	12.75 de	196.56 de	2.00	4.34
12	12.62 de	194.67 de	2.51	2.45
24	12.32 ef	189.91 ef	1.50	4.94
23	12.30 ef	189.75 ef	2.00	0.00
22	11.85 fg	182.80 fg	1.51	4.22
17	11.56 gh	178.28 gh	1.00	0.00
8	11.55 gh	178.16 gh	3.03	0.00
1	11.43 gh	176.21 gh	3.50	4.84
18	11.06 hi	170.60 hi	2.00	4.64
9	11.02 hi	169.90 hi	4.57	2.51
16	10.82 i	166.80 i	0.50	1.73
5	10.37 j	159.98 j	5.50	0.40
site mean	12.60	194.25	2.03	2.47
CV(%)	2.45	2.45	98.10	121.78
LSD(0.05)	0.44	6.75	2.82	4.27
LSD(0.01)	0.58	8.98	3.75	5.68
F-test	**	**	ns	**
RE(%)	----	----	----	104

** F-test significant at the 0.01 probability level, and ns = F-test not significant at the 0.05 probability level;

RE(%) = relative efficiency of the Simple Lattice Design over the Randomized Block Design, (---- = no efficiency).

‡ means followed by the same letter are not significantly different based on SNK's multiple range test at the 0.05 probability level.