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Selection of stable varieties by minimizing the probability of disaster[1]

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ABSTRACT

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Many plant breeders use estimates of stability parameters to aid them with making selections in the presence of cultivar×environment interaction. To make selections, the breeder must weight the importance of yield to stability. On the assumption that the plant breeder prefers varieties which minimize the probability of disastrously low yields, a general selection index is proposed which explicitly shows how the plant breeder weighs the importance of mean yield to stability. This index was applied to six international maize (*Zea mays* L.) yield trials using various stability models. Results indicated that the choice of a stability model can have a substantial effect on the desirability of a variety, and that inclusion of a measure of stability in the index may significantly alter the ranking of varieties compared with considering only the mean yield. The proposed index approach can be a practical way of making selections in the presence of cultivar×environment interaction when stability is a major concern.

INTRODUCTION

Making selections in the presence of cultivar×environment (*CE*) interaction is a major problem facing most crop breeders. *CE* interactions occur when the yield differences among cultivars are not of the same magnitude in different environments. Numerous stability measures of yield variability are available which can aid the plant breeder with identifying superior varieties in the presence of *CE* interaction (Lin et al., 1986). Use of these stability measures implicitly assumes that the plant breeder will weigh the importance of mean yield relative to stability when making selections. However, only a minimal amount of research has indicated explicitly how mean yield and stability might be combined to make selections (Barah et al., 1981; Eskridge, 1990). Consequently, plant breeders have been left to their own initiative to weigh the im-

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portance of stability relative to yield and to make final selections. If stability may be thought of simply as a measure of yield variability or uncertainty, then techniques for decision-making under risk may be used to model how the plant breeder chooses between varieties.

One group of decision-making models that may be used to quantify how a breeder weighs the importance of yield to stability is based on the assumption of safety-first behavior. Stated in terms of selection, plant breeders practice safety-first behavior if they are primarily concerned with the avoidance of disaster by choosing varieties which have a small chance of producing poor yields. Avoiding low yields is a consideration in any breeding program. It is likely, however, to be most important to breeders developing material which will be used by farmers who experience severe consequences as a result of low yields, e.g. subsistence farmers. These concepts readily apply to any plant-breeding program where *CE* interaction is a consideration, and where it is necessary to weigh the importance of yield relative to stability when making selections.

One safety-first model, which can be used to explicitly quantify how the breeder weighs the importance of yield to stability, was described by Roy (1952). Stated in terms of plant selection, Roy's safety-first approach is based on the assumption that the breeder specifies some minimum acceptable yield value, *d*, for all varieties under consideration, and then chooses the variety which has the smallest probability of producing a yield that is less than or equal to *d*. In this way, the breeder will choose a variety which minimizes the probability of 'disaster'. Yields below *d* will not necessarily result in a 'disaster' for all future users of the selected cultivar since farmers' practices and cost structures differ. For example, a subsistence farmer's disaster level, *d*, might be defined as the minimum yield necessary to feed the family, while a commercial farmer's disaster level might be the minimum yield required to meet variable costs of production.

If yields are normally distributed, it is shown in Appendix 1 that selecting a variety with the smallest probability of producing yields at or below *d* is the same as choosing a variety which has the largest value of:

$$[\bar{Y}_i - d]/V_i^{1/2} \qquad (1)$$

where: $\bar{Y}_i$ is the mean yield of the *i*th variety; *d*, the minimum acceptable yield level set for all varieties under test; and V_i is a variance measure of yield stability for the *i*th variety based upon an acceptable stability model. Equation (1) is simply the difference between the variety's mean and the disaster level, *d*, scaled by the square root of its stability measure. In this way, Roy's model explicitly quantifies how the plant breeder relates the importance of yield to stability and may be used to identify superior varieties. It should be noted that the assumption of normally distributed yields is consistent with assumptions which are made when selection is based on traditional criteria of mean yields, measures of error, and test of hypotheses based on analysis of variance.

The purpose of this paper is to show how Roy's safety-first model may be used to develop selection indices, each based on a different definition of stability, useful for selecting stable plant varieties, and to compare variety rankings by the various selection indices based on data from international maize (*Zea mays* L.) trials of the International Maize and Wheat Improvement Center (CIMMYT; Anonymous, 1990).

MATERIALS AND METHODS

Univariate stability models and selection indices

If Roy's safety-first model, as expressed in Eq. (1), is to be useful in aiding the plant breeder in making selections in the presence of *CE* interaction, it is necessary that V_i represent an acceptable measure of stability of the *i*th variety. Varietal stability will be based on three different models: (i) Shukla's (1972) stability variance; (ii) Eberhart and Russell's (1966) regression and deviation mean-square approach; and (iii) Finlay and Wilkinson's (1963) regression approach. These stability definitions will then be substituted into Eq. (1) to give three different selection indices, defined in Table 1.

To illustrate how the indices in Table 1 are obtained, let Y_{ij} represent the random yield of variety i ($i=1,...,p$) in environment j ($j=1,...,q$) with $\bar{Y}_{i\cdot}$, $\bar{Y}_{\cdot j}$, and $\bar{Y}_{\cdot\cdot}$ denoting the marginal means of variety i, environment j, and the overall mean, respectively. The different stability measures are then incorporated into Eq. (1) as follows.

Shukla's stability variance (SH). Shukla (1972) estimates p stability variance components where p is the number of varieties. Using this model, it is shown in Appendix 1 that yields adjusted for the average response to environment have the population mean and variance, μ_i and σ_i^2, where σ_i^2 is Shukla's population variance for the *i*th variety. The population mean yield μ_i is estimated with the sample mean, $\bar{Y}_{i\cdot}$, while σ_i^2 is estimated with $\hat{\sigma}_i^2$ from Shukla (1972). These estimates are then used in Eq. (1), which result in the SH index given in Table 1. Varieties with large mean yields ($\bar{Y}_{i\cdot}$) and small values of $\hat{\sigma}_i^2$ are preferred.

Eberhart and Russell's approach (ER). The relevant quantities in this approach are the *i*th variety's slope coefficient (β_i), estimated by regressing its yield on the mean yield of all cultivars for each environment, and the variance about regression ($\sigma_{\delta i}^2$). In this model, stability of the *i*th variety is measured by how far its β_i deviates from 1, and by the size of $\sigma_{\delta i}^2$. Plant breeders who use this approach commonly prefer varieties with large mean yields, slopes

TABLE 1

Selection indices which minimize the probability of disaster based on three different definitions of stability*

Stability definition	Index form for variety i	Abbreviation
Shukla's (1972) stability variance	$[\bar{Y}_{i\cdot}-d]/\hat{\sigma}_i$	SH
Eberhart and Russell's (1966) approach	$[\bar{Y}_{i\cdot}-d]/[(b_i-1)^2S^2_{\bar{y}}(1-1/q)+S^2_{\delta i}]^{1/2}$	ER
Finlay and Wilkinson's (1963) approach	$[\bar{Y}_{i\cdot}-d]/[(b_i-1)^2S^2_{\bar{y}}(1-1/q)]^{1/2}$	FW

*Let Y_{ij} be yield of the ith variety in the jth environment, where: $i=1,2,...,p$ and $j=1,2,...,q$. Then $\bar{Y}_{i\cdot}=\sum_j Y_{ij}/q$, $\bar{Y}_{\cdot j}=\sum_i Y_{ij}/p$, $\bar{Y}_{\cdot\cdot}=\sum_j\sum_j Y_{ij}/pq$,

$b_i=\sum_j(Y_{ij}-\bar{Y}_{i\cdot})(\bar{Y}_{\cdot j}-\bar{Y}_{\cdot\cdot})/\sum_j(\bar{Y}_{\cdot j}-\bar{Y}_{\cdot\cdot})^2$.

$S^2_{\bar{y}}=\sum_j(\bar{Y}_{\cdot j}-\bar{Y}_{\cdot\cdot})^2/(q-1)$,

$\hat{\sigma}^2_i=[p/((p-2)(q-1))]\sum_j(Y_{ij}-\bar{Y}_{i\cdot}-\bar{Y}_{\cdot j}+\bar{Y}_{\cdot\cdot})^2-SS(CE)/[(p-1)(p-2)(q-1)]$,

$S^2_{\delta i}=[1/(q-2)][\sum_j(Y_{ij}-\bar{Y}_{i\cdot})^2-b^2_i\sum_j(\bar{Y}_{\cdot j}-\bar{Y}_{\cdot\cdot})^2]$,

$SS(CE)=\sum_i\sum_j(Y_{ij}-\bar{Y}_{i\cdot}-\bar{Y}_{\cdot j}+\bar{Y}_{\cdot\cdot})^2$, and d is the 'disaster' limit.

close to 1 and small mean-square deviations about regression. Using this perspective, Eq. (1) could be used to weigh the importance of mean yield relative to Eberhart and Russell's stability, if a definition of variance could be developed which simultaneously measures how far a variety's slope deviates from 1 and the size of the mean square deviation about regression. In this model, the yield values, adjusted for the average yield response to environment, contain all the relevant information. As shown in Appendix 1, the adjusted yield of the ith variety has population mean μ_i and variance $(\beta_i-1)^2\sigma^2_{\bar{y}}(1-(1/q))+\sigma^2_{\delta i}$. This variance is large if the ith variety's slope differs substantially from 1, and/or its mean square deviation is large. The ith variety's mean and variance are estimated with $\bar{Y}_{i\cdot}$, and $(b_i-1)^2S^2_{\bar{y}}(1-(1/q))+S^2_{\delta i}$, respectively. The estimate $(b_i-1)^2S^2_{\bar{y}}(1-(1/q))+S^2_{\delta i}$ is substituted for V_i in Eq. (1) to give the ER index in Table 1.

Finlay and Wilkinson's Approach (FW). An index based on Finlay and Wilkinson's (1963) stability approach may be obtained from the ER index by setting $S^2_{\delta i}$ equal to zero for all cultivars (Table 1).

International maize variety trials

Data from six CIMMYT experimental variety yield trials (EVTs) were used to illustrate how the different indices could be applied, and how the different definitions of stability could affect the rankings of the varieties (Anonymous, 1990). Each EVT consisted of a different set of experimental open-pollinated varieties developed from CIMMYT Maize populations, plus two local controls. Because the local controls were different in each location, they were not included in the stability analyses. Descriptions of the trials are provided in Table 2. A randomized complete-block design with four replications was used at each location. Harvested plot size was 8.25 m^2, and population density was about 53 000 plants ha^{-1}, although these figures varied slightly among locations. Mean yields of the EVTs were generally in the 4-5 t ha^{-1} range, but with considerable variability over locations as indicated by the range of yield values (Table 2).

Data from these trials represent variation over locations, whereas the true measure of risk (or stability) to a farmer is variation over years at a given

TABLE 2

Description, number of entries, number of environments analyzed, and yield for six CIMMYT 1988 Experimental Variety Trials (EVTs)

EVT	Description of varieties	Varieties[a] (*n*)	Environments (*n*)	Yield (t ha^{-1})	
				Mean	Range
12	Tropical lowland, late maturity, white grain, developed from four populations	10	17	4.73	2.05–8.59
13	Tropical lowland, late maturity, yellow grain, developed from four populations	15	18	5.14	2.18–7.11
14A	Tropical lowland, early and intermediate maturity, yellow grain, developed from two populations	17	27	4.15	2.10–6.37
14B	Tropical lowland, early and intermediate maturity, white grain, developed from four populations	19	18	3.89	1.58–6.86
16A	Tropical mid-altitude, early and intermediate maturity, yellow grain, developed from four populations	15	11	4.52	1.58–7.96
16B	Tropical mid-altitude, intermediate and late maturity, white grain, developed from four populations	16	12	5.09	1.34–9.23

[a]Excluding local controls.

TABLE 3

Mean yield ($\bar{Y}_{i\cdot}$; t ha^{-1}), Finlay and Wilkinson's (1963) regression coefficient (b_i), Shukla's (1971) stability variance ($\hat{\sigma}_i^2$), Eberhart and Russell's (1966) deviation mean square ($S_{\delta i}^2$) and variance across environments ($S_{\bar{y}}^2$) for EVT 12 where estimates are computed over $q=17$ environments

Entry	$\bar{Y}_{i\cdot}$	b_i	$\hat{\sigma}_i^2$	$S_{\delta i}^2$
1	4.668	1.266	0.485	0.296
2	4.618	0.992	0.228	0.243
3	4.712	0.917	0.236	0.233
4	4.477	1.098	0.396	0.364
5	5.064	1.199	0.395	0.293
6	4.973	0.792	1.051	0.844
7	4.592	0.806	0.825	0.664
8	5.020	1.085	0.367	0.345
9	4.520	0.916	0.209	0.211
10	4.674	0.929	0.378	0.360

$S_{\bar{y}}^2=2.2014$.

location. Thus, the following assumptions have been made in this study: (1) that the same environmental factors that explain variation over sites in the sample also explain variability over years; and (2) that the variation across sites is similar to the variation over years. These assumptions are supported by the results in Barah et al. (1981).

Given estimates of each entry's mean yield and stability (Table 3 gives these values for EVT 12, for example), a selection index (Eq. (1)) computed for a particular definition of stability may be used to rank a set of entries, assuming that the breeder can set a reasonable value *d*. A crucial step in applying this approach is the choice of a disaster level *d*, which should always be based on the socioeconomic circumstances facing the target farmers. Small values of *d* would be used when high costs (bankruptcy, starvation, etc.) are associated with low yields, which is likely the case for many of the end-users of CIMMYT's cultivars. Larger values of *d* will generally produce rankings closer to those based on the mean yield, a situation where the farmer is not concerned with stability or risk. A value of $d=2$ t ha^{-1} is used to illustrate application of the indices.

To determine the sensitivity of entry rankings to different values of *d*, entry rankings for all EVTs are obtained when *d* was set at 3, 2, and 1 t ha^{-1}. Rank correlations were then calculated to quantify the similarity of entry orderings at different values of *d*.

RESULTS

To illustrate computations, index values for EVT 12 (Table 4) were calculated from the estimates in Table 3. Values for the three indices were com-

TABLE 4

Index values and rankings (in parentheses) for mean yield ($\bar{Y}_{i\cdot}$), and stability indices based on Finlay and Wilkinson's (1963) model (FW), Shukla's (1972) model (SH), and Eberhart and Russell's (1966) model (ER) for EVT 12, with $d=2$ t ha^{-1}

Entry	$\bar{Y}_{i\cdot}$*	FW	SH	ER
1	4.67 (6)	6.97 (10)	3.83 (8)	4.01 (7)
2	4.62 (7)	227.3 (1)	5.48 (3)	5.31 (2)
3	4.71 (4)	22.70 (4)	5.58 (1)	5.45 (1)
4	4.48 (10)	17.56 (6)	3.94 (7)	4.00 (8)
5	5.06 (1)	10.69 (7)	4.88 (5)	5.00 (5)
6	4.97 (3)	9.93 (8)	2.90 (9)	3.08 (9)
7	4.59 (8)	9.28 (9)	2.85 (10)	3.01 (10)
8	5.02 (2)	24.68 (3)	4.99 (4)	5.03 (4)
9	4.52 (9)	20.84 (5)	5.51 (2)	5.31 (3)
10	4.67 (5)	26.16 (2)	4.35 (6)	4.39 (6)

*Mean yield, t ha^{-1}.

TABLE 5

Rank correlations between indices based on mean yield ($\bar{Y}_{i\cdot}$), Finlay and Wilkinson's (1963) model (FW), Shukla's (1972) model (SH), and Eberhart and Russell's (1966) model (ER), with $d=2$ t ha^{-1}

EVT	Index	$\bar{Y}_{i\cdot}$	SH	ER
14B	SH	0.099		
14B	ER	0.099	0.977	
14B	FW	0.158	0.404	0.380
16B	SH	0.033		
16B	ER	0.033	0.967	
16B	FW	−0.200	0.333	0.300
12	SH	0.067		
12	ER	0.156	0.911	
12	FW	0.022	0.511	0.511
13	SH	0.410		
13	ER	0.410	1.000	
13	FW	0.219	0.543	0.543
14A	SH	0.412		
14A	ER	0.441	0.970	
14A	FW	−0.029	−0.118	−0.118
16A	SH	0.086		
16A	ER	0.124	0.962	
16A	FW	0.219	0.257	0.257

puted for each entry in all six EVTs. For all EVTs, Kendall's Tau rank correlations between the indices' rankings (Snedecor and Cochran, 1967), when $d=2$ t ha^{-1}, quantify the similarity of entry orderings (Table 5). The SH and ER indices produce nearly identical entry rankings for all EVTs considered

TABLE 6

Rank correlations between indices based on Finlay and Wilkinson's (1963) model (FW), Shukla's (1972) model (SH), and Eberhart and Russell's (1966) model (ER) calculated with $d=3$ t ha^{-1} and other values of d when the indices are based on the same definition of stability

EVT	d (t ha^{-1})	$d=3$ t ha^{-1}		
		SH	ER	FW
14B	2	0.836	0.813	0.930
14B	1	0.731	0.684	0.906
16B	2	0.950	0.950	1.000
16B	1	0.917	0.917	0.967
12	2	0.867	0.778	0.956
12	1	0.778	0.644	0.956
13	2	0.962	0.943	0.989
13	1	0.924	0.905	0.981
14A	2	0.809	0.824	0.956
14A	1	0.735	0.735	0.941
16A	2	0.733	0.695	0.810
16A	1	0.562	0.524	0.733

(rank correlation >0.90). Pham and Kang (1988) found similar results when correlating various stability measures based on CIMMYT maize data. For most EVTs, the FW index produces rankings which are substantially different from the SH and ER indices (rank correlation <0.4 for most EVTs). These inconsistent rankings are caused by the denominator in FW being so much smaller than the denominators in the SH and ER indices because of the exclusion of the deviations from regression term. Use of FW ignores a substantial amount of variation which is accounted for in the SH and ER indices. In addition, the mean yield ($\bar{Y}_{i\cdot}$) produces rankings different from FW, SH and ER as indicated by most rank correlations being less than 0.4. Thus, the inclusion of a measure of stability (or risk) may alter quite markedly the ranking of varieties compared to considering only the mean yields. This observation is consistent with Barah et al. (1981).

For each index, the sensitivity of the entry rankings to changing d is quantified with rank correlations (Table 6). Entry rankings based on indices with $d=3$ t ha^{-1} are correlated with entry rankings obtained from indices with $d=2$ and 1 t ha^{-1}. For the SH and ER indices, rank correlations for most EVTs are larger than 0.7, indicating fairly consistent entry orderings for all three values of d. FW entry rankings are quite consistent for all values of d, as indicated by most rank correlations being larger than 0.9. FW entry rankings appear to be less sensitive to changes in d than do ER and SH entry rankings, since the values of the FW index are substantially larger than the index values of either the ER or SH.

DISCUSSION AND CONCLUSION

If the plant breeder is assumed to make choices by minimizing the probability of disaster, and yields are assumed to be normally distributed, then index (1) represents how the breeder weighs the importance of yield to stability. However, if index (1) is to be useful in selecting for genotypic stability, the breeder must specify the disaster level *d*, and choose a definition of stability. Entry rankings will depend on the specified values of *d* and the chosen definition of stability.

Choice of a disaster level. When using any of the indices in Table 1, choice of an appropriate disaster level, *d*, should be carefully considered. It is important to emphasize that the *d* value should be chosen to accurately reflect the disaster level of the target farmers. Small values of *d*, which usually are associated with small probabilities of yield falling below *d*, generally reflect a strong desire to avoid the risk of low yields. Ideally, the plant breeder would survey the farmers for whom the breeding program is targeted and determine some average or median value of *d*. If direct elicitation is not possible, it may be possible to use previous research on the target farmers to determine the minimum acceptable yield level for an 'average farm'. If this approach is not possible, entry rankings should be obtained for a reasonable range of *d* values with consistently high-ranking entries being preferred.

Choice of a stability measure. The choice of an appropriate stability measure must also be carefully considered (see Lin et al. (1986) for a good discussion of the different types of stability measures). The stability measures used in this study are b_i, $\hat{\sigma}_i^2$, and $S_{\delta i}^2$; b_i and $\hat{\sigma}_i^2$ measure Type 2 stability, where a variety is considered stable if its response to environment is parallel to the average response of all varieties in the test. This type of stability can be useful when the trial is conducted over a diverse set of environments. However, Type 2 stability is a relative measure which depends on the varieties in the trial, and thus statements based on this type of stability must be restricted to only those varieties being tested. Consequently, the FW and SH indices may be useful for evaluating a given set of varieties relative to one another over a broad range of environments, but extreme care should be exercised when using these indices to make inferences about varieties not in the test.

Type 3 stability ($S_{\delta i}^2$) ideally measures unpredictable irregularities of a variety's response to environment, in contrast to Type 2 which measures the 'predictable' response to environment. The ER index includes both Type 2 and 3 stability and thus can be used, as FW and SH, to compare a given set of varieties over a broad range of environments. By including both Type 2 and 3 stabilities, ER is a more comprehensive index than either FW or SH. However, use of $S_{\delta i}^2$ as a measure of Type 3 stability has been criticized, since the independent variable is not measured prior to the experiment (Lin et al., 1986), and because $S^2_{\delta i}$ usually has a large standard error when the trial is not conducted in a large number of environments. Also, unqualified preference for small values of $S^2_{\delta i}$ may be dangerous. For example, large positive deviations from regression may indicate a unique disease resistance in an otherwise disease-ridden low-yielding environment. Selections based on small values of $S^2_{\delta i}$ could eliminate a very promising source of disease resistance. In addition, a further criticism of the ER index is the entry rankings based on this index are sensitive to the specified value of d.

These disadvantages of the ER index appear to make the FW index somewhat more attractive. With the FW index, b_i is usually estimated with a fair degree of precision, even with a moderate number of environments, and entry rankings based on FW are not sensitive to different values of d. Yet the FW index may have limited usefulness since b_i values very close to 1 may result in unrealistically large index values.

In summary, if the environmental index in ER could be replaced by actual environmental factors such as temperature or rainfall, if $\sigma^2_{\delta i}$ could be precisely estimated, and if a meaningful value of d could be obtained, ER would clearly be the preferred index of those presented.

Comparison with other selection approaches that combine both mean yield and stability measures. Minimizing the probability of disaster compares favorably with other approaches that may be used to explicitly combine both mean yields and stability when making selections. Barah et al. (1981) used an expected returns/variance (E/V) framework to identify risk efficient sorghum varieties. The E/V approach is a special case of the expected utility model, which is based on a complicated set of assumptions. The behavioral assumptions of Roy's model are much simpler, in that the breeder is concerned only with avoiding yields below the disaster level d. Menz (1980) used stochastic dominance (SD) to categorize wheat varieties as risk-efficient or risk-inefficient. SD is more comparable to Roy's approach in that it is based on less stringent behavioral assumptions than the E/V approach. However, plant breeders commonly desire a complete ranking of all varieties under test. Minimizing the probability of disaster produces a complete ranking, while SD generally does not. Eskridge (1990) used a lower-confidence-interval approach to identify stable high-yielding maize varieties. This approach requires that a lower confidence bound or disaster level be estimated for each variety. Roy's approach is more direct than the lower-confidence-interval approach, since a single disaster level d is set for all varieties.

There appear to be several additional advantages to using Roy's safety-first approach. First, this approach produces a simple index (1) which is based on the reasonable assumption that the plant breeder makes choices to minimize the probability of disaster. Second, assuming the breeder makes choices to minimize the probability of disaster, the model can be used as a decision-making tool which explicitly shows how the plant breeder values yield to stability. Third, stability may be defined by any one of several univariate stability models commonly used by plant breeders. Finally, once a stability measure has been chosen, entry rankings based on this approach appear to be fairly insensitive to different disaster values.

However, there are several limitations which must be kept in mind when applying Roy's safety-first approach to selecting for genotypic stability. Identifying the best value of d may be quite difficult, especially if the target farmers are quite heterogeneous. Also, if the trials of interest are not conducted in a large number of environments, the stability parameters may be estimated with a relatively low degree of precision, producing entry rankings of questionable value. Thirdly, the low correlations of these indices with the mean yield indicate that, when $d=2$ t ha^{-1}, yield per se had a smaller influence on index values than did the stability parameters. Thus, with $d=2$ t ha^{-1}, it would appear that this method has the greatest applicability in situations where stability of yield was an overriding concern. Finally, since the index is a ratio, more research is needed to evaluate the effects of incorporating economic factors, such as production costs, into the index.

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APPENDIX 1

Roy's Safety-first Model. Assume that yields for the ith variety are normally distributed with population mean μ_i and variance σ_i^2. Also assume that $d<\mu_i$ for all varieties. Using Roy's model, the variety which minimizes $P(Y_i \leq d)$ is preferred. But note:

$$P(Y_i \leq d) = P([Y_i - \mu_i]/\sigma_i \leq [d-\mu_i]/\sigma_i)$$
$$= F([d-\mu_i]/\sigma_i)$$

where $F(.)$ is the standard normal cumulative distribution function. Thus, the variety which minimizes $F([d-\mu_i]/\sigma_i)$ also maximizes $F([\mu_i-d]/\sigma_i)$, and since $F(.)$ is an increasing one-to-one function, choosing the variety with the largest value of $F([\mu_i-d]/\sigma_i)$ is the same as choosing the variety with the maximum value of $[\mu_i-d]/\sigma_i$. In practice, μ_i is estimated with $\bar{Y}_{i\cdot}$, the sample mean yield, and σ_i is estimated with $V_i^{1/2}$, the square root of the sample variance based on an acceptable-stability model. Thus, using the trial information, the variety with the largest value of $[\bar{Y}_{i\cdot} - d]/V_i^{1/2}$ will be preferred.

Shukla's stability variance. Following Shukla (1972), define the following model:

$$Y_{ij} = \mu + C_i + E_j + CE_{ij}$$

where μ is the grand mean, C_i is the fixed effect of variety i, E_j and CE_{ij} are environment and CE interaction effects. The breeder is generally not interested in the environmental effect E_j, since it contains no information about the ith variety. Thus, yield is 'adjusted' by subtracting E_j from both sides of the equality, giving:

$$YA_{ij} = \mu + C_i + CE_{ij}$$

where YA_{ij} represents the adjusted yield. CE_{ij} is then assumed to be normally and independently distributed with expectation 0, and variance σ_i^2. Using rules of expectation and variance, and taking expectations over all environments for variety i, the population mean and variance of the adjusted yield for variety i are $\mu + C_i = \mu_i$ and σ_i^2, respectively.

Eberhart and Russell's approach. This method characterizes the value of a variety by its mean yield μ_i, how far its regression coefficient (β_i) deviates from 1, and the size of the mean square deviation about regression ($\sigma_{\delta i}^2$). Following Eberhart and Russell (1966), define the following model:

$$Y_{ij} = \mu_i + \beta_i(\bar{Y}_{\cdot j} - \bar{Y}_{\cdot\cdot}) + \delta_{ij}$$

where μ_i is the population mean yield of the ith variety, β_i is Finlay and Wilkinson's (1963) population regression coefficient, $\bar{Y}_{\cdot j}$ the marginal mean of environment j which is assumed to be a random variable with true mean $\mu_{\bar{y}}$ and variance $\sigma_{\bar{y}}^2$, and δ_{ij} is a normally and independently distributed error with mean 0, and variance $\sigma_{\delta i}^2$. By adding and subtracting the product of the mean slope (β) and the 'environment index', $\beta(\bar{Y}_{\cdot j} - \bar{Y}_{\cdot\cdot})$, to the right side of this equation, we obtain:

$$Y_{ij} = \mu_i + \beta(\bar{Y}_{\cdot j} - \bar{Y}_{\cdot\cdot}) + (\beta_i - \beta)(\bar{Y}_{\cdot j} - \bar{Y}_{\cdot\cdot}) + \delta_{ij}.$$

But $\beta(\bar{Y}_{\cdot j} - \bar{Y}_{\cdot\cdot})$ contains no information about the ith variety, since it represents how the average variety responds to the environment index. Therefore, subtracting $\beta(\bar{Y}_{\cdot j} - \bar{Y}_{\cdot\cdot})$ from both sides of the equation gives the following 'adjusted' yield (YA_{ij}) which contains all the useful information about the ith variety considered important by Eberhart and Russell's approach:

$$YA_{ij} = \mu_i + (\beta_i - \beta)(\bar{Y}_{\cdot j} - \bar{Y}_{\cdot\cdot}) + \delta_{ij}$$

Since the mean slope (β) is always 1, and using the rules of expectation and variance, the population mean and variance over environments of the adjusted yield for the *i*th variety can be shown to be μ_i and $(\beta_i - 1)^2\sigma_{\bar{y}}^2(1-(1/q))+\sigma_{\delta i}^2$, respectively, where q is the number of environments in the trial.

REFERENCES

Anonymous, 1990. CIMMYT International Maize Testing Program. 1988 Preliminary Report. CIMMYT, El Batan, Mexico (in press).

Barah, B.C., Binswanger, H.P., Rana, B.S. and Rao, N.G.P., 1981. The use of risk aversion in plant breeding: concept and application. Euphytica, 30: 451–458.

Eberhart, S.A. and Russell, W.A., 1966. Stability parameters for comparing varieties. Crop Sci., 6: 36–40.

Eskridge, K.M., 1990. Selection of stable cultivars using a safety-first rule. Crop Sci., 30: 369–374.

Finlay, K.W. and Wilkinson, G.N., 1963. The analysis of adaptation in a plant-breeding programme. Aust. J. Agric. Res., 14: 742–754.

Lin, C.S., Binns, M.R. and Lefkovitch, L.P., 1986. Stability analysis: Where do we stand? Crop Sci., 26: 894–899.

Menz, K.M., 1980. A comparative analysis of wheat adaptation across international environments using stochastic dominance and pattern analysis. Field Crops Res., 3: 33–41.

Pham, H.N. and Kang, M.S., 1988. Interrelationships among and repeatability of several stability statistics estimated from international maize trials. Crop Sci., 28: 925–928.

Roy, A.D., 1952. Safety-first and the holding of assets. Econometrica, 20: 431–449.

Shukla, G.K., 1972. Some statistical aspects of partitioning genotype-environmental components of variance. Heredity, 29: 237–245.

Snedecor, G.W. and Cochran, W.G., 1967. Statistical methods. (6th edition). Iowa State Univ. Press, Ames.