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Kent M. Eskridge
University of Nebraska-Lincoln, keskridge1@unl.edu

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ABSTRACT

The presence of genotype by environment interaction is of major concern to plant breeders, since large interactions can reduce gains from selection and complicate identification of superior cultivars. Numerous statistics have been proposed to characterize stability of cultivars, yet none of these methods explicitly indicate how stability may be combined with mean yield in choosing superior cultivars. It is assumed that the plant breeder prefers a cultivar with a small probability of low yield. Using a decision-theory concept known as *safety-first* to model such behavior, an index incorporating mean yield and stability is developed for each of four different definitions of stability. Data from an international experimental maize (*Zea mays* L.) yield trial are used to illustrate the application of these indices when genotype by environment interaction is present. It is concluded that safety-first selection indices can be useful to plant breeders when genotype by environment interaction is large and poor yield has severely adverse consequences.

MOST PLANT BREEDERS are concerned with selecting cultivars that perform well in a wide range of environments. However, identification of such broadly-adapted cultivars becomes difficult when the phenotypic response to a change in environment varies among entries being tested. This genotype by environment (GE) interaction can reduce progress from selection (Comstock and Moll, 1963) and can cause difficulty in identifying superior cultivars.

Numerous stability methods are available to aid the plant breeder with identifying superior cultivars in the presence of GE interaction (see Lin et al., 1986, for a review of these methods). All these approaches provide information that allows the breeder to rank or classify cultivars by levels of adaptability. This paper will be concerned with univariate stability techniques that characterize genotypic adaptability by use of one or more stability statistics.

When making selections in the presence of GE interaction, the breeder must weigh the importance of a cultivar's stability relative to its mean yield across environments. Plaisted and Peterson (1959) suggested that in addition to comparing means, the plant breeder should use each cultivar's relative contribution to the GE variance component to "measure its dependability." Finlay and Wilkinson (1963) suggested using a cultivar's regression coefficient of yield response to environment as well as the mean yield to characterize the cultivar's desirability. Eberhart and Russell (1966) used mean yield, Finlay and Wilkinson's regression coefficient, and deviations from regression to identify stable hybrids. Shukla (1972) proposed estimating an unbiased "stability variance" for each cultivar, implying that both the mean yield and stability variance be used to characterize the desirability of a cultivar.

None of these authors explicitly indicate how to develop a usable index based on both mean yield and stability parameter(s). Plant breeders are left on their own to weigh the importance of stability relative to yield in making their final choices.

What is needed is a decision making tool which explicitly quantifies how a plant breeder weighs the importance of yield relative to stability. If stability may be thought of simply as a measure of variability or uncertainty, then techniques for decision making under risk can be used to develop stability indices which weigh the importance of yield to stability (see Chapter 5 in Hazell and Norton, 1986, for an introduction to many of these techniques).

One group of decision making techniques that may be used to develop an index based on mean yield and stability is based on the assumption of *safety-first behavior.* Models based on safety-first behavior were first presented in the economic literature as a means of modeling how people make financial investment decisions when severe consequences (e.g., bankruptcy) are possible (Roy, 1952; Telser, 1955; Berck and Hihn, 1982; Atwood, 1985). Though safety-first models often could be simply applied to agronomic selection problems, agronomists generally have not used these methods.

Stated in terms of selection, if a plant breeder is primarily concerned with the avoidance of disaster, he/she could practice safety-first behavior by choosing

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cultivars which have a small chance of producing poor yields. Avoiding low yields is important to both producers and marketers of cultivars at any production level; however, it may be more important to breeders developing material that will be used by farmers who experience severe consequences as a result of low yields (e.g., subsistence farmers).

Nevertheless, the major importance of safety-first behavior is that the resulting decision models may be used to develop indices that quantify how a plant breeder weighs the importance of yield to stability when developing cultivars for a broad range of environments. In situations where there are sufficient funds and economic justification to breed for a particular environment, stability is irrelevant and yield in that environment is paramount. However, if cultivars are being selected for a large group of environments then stability and mean yield across all environments are of major importance and yield in a specific environment is of marginal importance.

Several safety-first models can be applied to plant breeding problems. A model proposed by Kataoka (1963) has intuitive appeal and can be simply applied to plant selection. The breeder would first specify some acceptable probability (α) of having a disastrously low yield (say, a 1 in 20 chance or $\alpha = 0.05$). Using this α, a lower confidence limit would be computed for each cultivar. A cultivar's lower confidence limit would represent the yield level for which lower yields would occur with only an α% chance. Cultivars with large lower confidence limits would be preferred. If stability can be thought of as a measure of variance, then the breeder selecting for stability would prefer cultivars with large values of

$$\bar{Y}_{i\cdot} - Z(1 - \alpha)\,(V_i)^{1/2} \qquad [1]$$

where $\bar{Y}_{i\cdot}$ is the sample mean yield across environments for cultivar i, V_i is some measure of stability for cultivar i and $Z(1 - \alpha)$ is the $1 - \alpha$ percentile from the standard normal distribution (see Appendix). In this way Kataoka's safety-first model can be used to obtain an index which explicitly quantifies how the breeder might weigh the relative importance of yield and stability.

Another safety-first model that might be applied to plant selection was proposed by Roy (1952). In terms of plant selection, the breeder would specify some minimum acceptable yield value (d) for all cultivars under consideration. Cultivars with the smallest chance of producing a disastrous yield below d would be preferred. Use of this model would result in basing selections on an index similar to the coefficient of variation. In a way, Roy's approach is more direct than Kataoka's, since a single minimum acceptable yield value is set for all cultivars. However, because the index is a ratio, cultivar rankings based on this approach may be quite sensitive to seemingly irrelevant factors such as production costs even if these factors are the same for all cultivars in all environments. Consequently, this paper will apply only Kataoka's lower confidence limit approach.

This paper will illustrate how Kataoka's safety-first model may be used to quantify the relative importance of yield to stability, and to develop selection indices for several definitions of stability. Cultivar rankings by the various selection indices will be compared based on stability estimates computed from a multi-environment yield trial.

MATERIALS AND METHODS

If the safety-first selection index Eq. [1] is to be useful in aiding the plant breeder in making selections in the presence of GE interaction, V_i must represent an acceptable measure of stability of the ith cultivar. Cultivar stability will be based on four different models: (i) the variance of a cultivar across environments (EV), (ii) Finlay and Wilkinson's (1963) regression coefficient (FW), (iii) Shukla's (1972) stability variance (SH), and (iv) both Finlay and Wilkinson's regression coefficient and Eberhart and Russell's (1966) deviation parameter (ER) (Table 1).

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

Variance of a cultivar across environments. This approach simply involves use of the variance of a cultivar across environments as a measure of stability. The true mean of the ith cultivar across environments is μ_i with variance across environment σ^2_{io}. The μ_i and σ^2_{io} are estimated with $\bar{Y}_{i\cdot}$ and $S^2_{i\cdot}$. These estimates are substituted for $\bar{Y}_{i\cdot}$ and V_i in Eq. [1], giving the index denoted EV in Table 1. Using this index, cultivars with large mean yields and small standard deviations across environments will be preferred.

Finlay and Wilkinson's approach. The relevant quantity in this approach is the ith cultivar's slope coefficient (β_i) obtained by regressing its yield on the mean yield of all cultivars for each environment. In this model, stability of the ith cultivar is measured by how far its β_i deviates from 1. A cultivar with a large mean yield and a slope close to 1 is preferred. Equation [1] could be used to weigh the importance of mean yield relative to Finlay and Wilkinson's stability if a definition of variance could be developed to measure how far a cultivar's slope deviates from 1. In this model, the predicted yield values, adjusted for the average yield response to environment, contain all the relevant information. As shown in the Appendix, the adjusted predicted yield of the ith cultivar has population mean μ_i and variance $(\beta_i - 1)^2\,\sigma^2_{\bar{y}}\,(1 - 1/q)$. This variance represents that portion of the ith cultivars's total variance of its predicted yield which is due to its slope coefficient differing from 1. The population mean and variance are estimated with $\bar{Y}_{i\cdot}$ and $(b_i - 1)^2\,S^2_{\bar{y}}\,(1 - 1/q)$, respectively. The estimated variance, $(b_i - 1)^2\,S^2_{\bar{y}}\,(1 - 1/q)$, is then substituted for V_i in Eq. [1] to give the FW index in Table 1. When all cultivars have a slope of 1, the FW index reduces to the mean yield.

Shukla's stability variance. Shukla (1972) estimates a stability variance component for each of p cultivars. Using this model, the population mean and variance of cultivar i are μ_i and $\sigma^2_E + \sigma^2_i$ where σ^2_E and σ^2_i are the variance of the random effects of environment and Shukla's population variance for the ith cultivar, respectively (see Appendix). The population mean yield for cultivar i, μ_i, is estimated with the sample mean, $\bar{Y}_{i\cdot}$, σ^2_i is estimated with $\hat{\sigma}^2_i$ from Shukla (1972), and σ^2_E is estimated with the standard ANOVA estimator; $\hat{\sigma}^2_E + \hat{\sigma}^2_i$ is then substituted for V_i in Eq. [1], which results in the SH index in Table 1.

Eberhart and Russell's approach. This approach characterizes the desirability of a cultivar using three parameters: its mean yield (μ_i), Finlay and Wilkinson's regression coefficient (β_i), and the mean square deviations about regression ($\sigma^2_{\delta i}$). Using reasoning similar to that in derivation of the FW index, it is shown in the Appendix that the population mean and variance for cultivar i using Eberhart and Russell's

Table 1. Safety-first selection indices with four definitions of stability.†

Stability definition	Index form for cultivar i	Abbreviation
Variance across environments	$\bar{Y}_{i.} - Z(1-\alpha)\,S_i$	EV
Finlay and Wilkinson's regression coefficient	$\bar{Y}_{i.} - Z(1-\alpha)\,[(b_i - 1)^2\,S_{\bar{y}}^2\,(1 - 1/q)]^{1/2}$	FW
Shulka's stability variance	$\bar{Y}_{i.} - Z(1-\alpha)\,[\hat{\sigma}_E^2 + \hat{\sigma}_i^2]^{1/2}$	SH
Finlay and Wilkinson's regression coefficient and Eberhart and Russell's residual MS about regression	$\bar{Y}_{i.} - Z(1-\alpha)\,[(b_i - 1)^2\,S_{\bar{y}}^2\,(1 - 1/q) + S_{\delta i}^2]^{1/2}$	ER

† $\bar{Y}_{i.} = \sum_{j=1}^{q} Y_{ij}/q$; $\bar{Y}_{.j} = \sum_{i=1}^{p} Y_{ij}/p$; $\bar{Y}_{..} = \sum_{i=1}^{p}\sum_{j=1}^{q} Y_{ij}/pq$; where Y_{ij} = yield of ith cultivar in jth environment, $i = 1,2,\ldots,p$; $j = 1,2,\ldots,q$;

$Z(1-\alpha) = 1-\alpha$ percentile from the standard normal distribution;

$S_i^2 = \sum_{j=1}^{q} (Y_{ij} - \bar{Y}_{i.})^2/(q-1)$;

$b_i = \sum_{j=1}^{q} (Y_{ij} - \bar{Y}_{i.})(\bar{Y}_{.j} - \bar{Y}_{..}) / \sum_{j=1}^{q} (\bar{Y}_{.j} - \bar{Y}_{..})^2$;

$S_{\bar{y}}^2 = \sum_{j=1}^{q} (\bar{Y}_{.j} - \bar{Y}_{..})^2/(q-1)$;

$\hat{\sigma}_E^2 = [\mathrm{MS(E)} - \mathrm{MS(GE)}]/p$; where

$\mathrm{MS(E)} = p\sum_{j=1}^{q} (\bar{Y}_{.j} - \bar{Y}_{..})^2/(q-1)$;

$\mathrm{SS(GE)} = \sum_{i=1}^{p}\sum_{j=1}^{q} (Y_{ij} - \bar{Y}_{i.} - \bar{Y}_{.j} + \bar{Y}_{..})^2$;

$\mathrm{MS(GE)} = \mathrm{SS(GE)}/(p-1)(q-1)$;

$\hat{\sigma}_i^2 = \{p/[(p-2)(q-1)]\}\sum_{j=1}^{q}(Y_{ij} - \bar{Y}_{i.} - \bar{Y}_{.j} + \bar{Y}_{..})^2; - \mathrm{SS(GE)}/[(p-1)(p-2)(q-1)]$;

$S_{\delta i}^2 = [1/(q-2)][\sum_{j=1}^{q} (Y_{ij} - \bar{Y}_{i.})^2 - b_i^2 \sum_{j=1}^{q} (\bar{Y}_{.j} - \bar{Y}_{..})^2]$.

Table 2. Entries and maturity classification of 1984 CIMMYT Experimental Variety Trial 14B.

No.	Entry	Population description	Maturity
1	Ferke(1) 8223†	Tropical white flint	Medium
2	Poza Rica 8223	Tropical white flint	Medium
3	Kolhapur 8130	Tropical white flint/semi-flint	Early
4	Across 8132	Mix of tropical/temperate flints	Med-late
5	Los Banos 8232	Mix of tropical/temperate flints	Med-late
6	Los Banos(1) 8232	Mix of tropical/temperate flints	Med-late
7	Poza Rica 8232	Mix of tropical/temperate flints	Med-late
8	San Jeronimo 8232	Mix of tropical/temperate flints	Med-late
9	Ikenne(1) 8149	Tropical/subtropical white dent	Medium
10	Gandankia 8149	Tropical/subtropical white dent	Medium
11	Pirsabak(1) 7930RE	Tropical white flint/semi-flint	Early
12	Los Diamantes 7823RE	Tropical white flint	Medium

† The first two digits identify the year the family was selected and the last two digits denote the CIMMYT parent population number.

Table 3. Mean yield ($\bar{Y}_{i.}$), variance across environments, (S_i^2), Finlay and Wilkinson's regression coefficient (b_i), Shukla's stability variance ($\hat{\sigma}_i^2$), and Eberhart and Russell's deviation mean square from regression ($S_{\delta i}^2$) for entries, and variance of environment means ($S_{\bar{y}}^2$) and environmental variance component ($\hat{\sigma}_E^2$) in 1984 CIMMYT Experimental Variety Trial 14B.

Entry	$\bar{Y}_{i.}$	S_i^2	b_i	$\hat{\sigma}_i^2$	$S_{\delta i}^2$
	Mg ha^{-1}				
1	4.69	2.22	1.08	0.02	0.03
2	4.49	2.21	1.05	0.14	0.15
3	3.93	1.81	0.92	0.24	0.23
4	4.16	1.51	0.84	0.24	0.19
5	4.20	2.77	1.15	0.41	0.35
6	4.54	2.57	1.12	0.26	0.23
7	4.62	3.22	1.27	0.37	0.20
8	4.65	3.13	1.22	0.48	0.36
9	4.68	1.27	0.76	0.33	0.21
10	4.53	1.74	0.91	0.22	0.21
11	3.86	0.94	0.65	0.42	0.16
12	4.60	1.65	1.00	0.26	0.28
	$S_{\bar{y}}^2 = 1.87$		$\hat{\sigma}_E^2 = 1.80$		

model are μ_i and $(\beta_i - 1)^2\,\sigma_{\bar{y}}^2\,(1 - 1/q) + \sigma_{\delta i}^2$, respectively. The variance term $(\beta_i - 1)^2\,\sigma_{\bar{y}}^2(1-1/q) + \sigma_{\delta i}^2$ represents that portion of the ith cultivar's total variance which is due to its slope coefficient differing from 1 and due to its deviations about its regression line. μ_i and $(\beta_i - 1)^2\sigma_{\bar{y}}^2(1-1/q) + \sigma_{\delta i}^2$ are estimated with $\bar{Y}_{i.}$ and $(b_i - 1)^2\,S_{\bar{y}}^2\,(1 - 1/q) + S_{\delta i}^2$. The estimate $(b_i - 1)^2\,S_{\bar{y}}^2\,(1 - 1/q) + S_{\delta i}^2$ is substituted for V_i in Eq. [1] to give the ER index in Table 1.

Maize yield data from the International Maize and Wheat Improvement Center's (CIMMYT) 1984 Experimental Variety Trial 14B were used as an example of how different definitions of stability affect entry rankings when using the safety-first selection index (Table 2). Each entry is a composite cross formed from the 10 best families from a CIMMYT population tested at a particular international test site or from the 10 best families averaged across all environments in the international progeny testing program. The entry name indicates the location and year where the 10 best families were identified and selected for recombination. In addition, the last two digits denote the CIMMYT parent population number. Experimental Variety Trial 14B was evaluated in 15 locations throughout the world (CIMMYT, 1985).

Given estimates of each entry's mean yield and stability (Table 3), the safety-first selection index (Eq. [1]) for a particular definition of stability may be used to rank a set of entries, assuming the breeder can specify a reasonable value of α. A particular value of α [or of $Z(1-\alpha)$] indicates the breeder's willingness to accept low yields expressed in terms of probability. Small values of α would be used when high costs (bankruptcy, starvation, etc) are associated with low yields, which likely is the case for subsistence farmers. Since the end users of CIMMYT's material are generally subsistence farmers, a value of $\alpha = 0.05$ [$Z(0.95) = 1.645$] is used to illustrate entry orderings when low yields have severe consequences. The $\alpha = 0.05$ translates into a willingness to accept a one in 20 chance of a low yield in a particular season.

Table 4. Values of four safety-first selection indices and associated rankings (in parentheses).

Entry	Mean yield	EV†	FW	SH	ER
	Mg ha^{-1}				
1	4.69(1)	2.24(5)	4.52(2)	2.47(1)	4.34(1)
2	4.49(8)	2.04(7)	4.38(3)	2.20(4)	3.85(2)
3	3.93(11)	1.72(10)	3.76(11)	1.58(11)	3.12(11)
4	4.16(10)	2.14(6)	3.81(10)	1.81(9)	3.35(9)
5	4.20(9)	1.46(12)	3.87(9)	1.75(10)	3.18(10)
6	4.54(6)	1.90(8)	4.28(5)	2.18(7)	3.70(6)
7	4.62(4)	1.67(11)	4.03(8)	2.20(5)	3.67(7)
8	4.65(3)	1.74(9)	4.17(6)	2.17(8)	3.55(8)
9	4.68(2)	2.83(1)	4.16(7)	2.28(2)	3.78(3)
10	4.53(7)	2.36(3)	4.33(4)	2.19(6)	3.76(4)
11	3.86(12)	2.26(4)	3.10(12)	1.41(12)	2.86(12)
12	4.60(5)	2.49(2)	4.60(1)	2.24(3)	3.73(5)

† EV = safety-first index with variance across environments as stability parameter, FW = safety-first index with Finlay and Wilkinson's regression coefficient as stability parameter, SH = safety-first index with Shukla's stability variance as stability parameter, and ER = safety-first index with Finlay and Wilkinson's regression coefficient and Eberhart and Russell's deviation mean square as stability parameters.

RESULTS

Safety-first index values (Table 4) were computed from the estimates given in Table 3. These index values are useful only if there is reason to believe that the means and stability parameters differ. Using tests suggested by Eberhart and Russell (1966), the hypotheses of homogeneous entry means and homogeneous entry regression coefficients were both rejected ($P < 0.01$). In addition, using Hartley's F max test (Neter and Wasserman, 1974), the hypotheses of equality of Shukla's stability variances and equality of Eberhart and Russell's deviation mean squares were both rejected ($P < 0.01$). Following Shukla (1972), approximate variances for the stability parameters b_i, $\hat{\sigma}_i^2$, and $S_{\delta i}^2$ can be computed using $S_{\delta i}^2/[(q-1)S_y^2]$, $2\hat{\sigma}_i^2/(q-1)$, and $2S_{\delta i}^2/(q-2)$, respectively, where q is the number of environments.

Kendall's tau rank correlations (Snedecor and Cochran, 1967) between the mean and index rankings quantify how similarly the indices rank the entries (Table 5). The FW, SH, and ER indices all produce similar entry rankings (rank correlation > 0.65). Similar rankings produced by FW and SH would be expected, since both indices define stability to be Type 2 (Lin et al., 1986). Likewise, the ER index would be expected to produce rankings similar to FW and SH since the ER index also uses a Type 2 stability measure (b_i) in addition to a Type 3 measure ($S_{\delta i}^2$). An entry with Type 2 stability has a response parallel to all entries' responses; entries with Type 3 stability have a small mean square deviation from regression on the environment means (Lin et al., 1986).

The EV index produces rankings which are poorly correlated (rank correlation < 0.37) with those of the other indices. This result would be expected, since the EV index defines stability as across-environment yield variance, S_i^2 (Type 1 stability as defined by Lin et al., 1986), which is not likely to be closely related to the measures of stability used by the other indices. These findings are supported by Pham and Kang (1988), who found similar results when correlating various stability measures based on CIMMYT maize data.

The mean ranking is poorly correlated (rank correlation < 0.16) with the EV ranking. Such a low rank correlation reflects the fact that the EV index is

Table 5. Kendall rank correlations between entry rankings from four selection indices.

	Mean	EV†	FW	SH
EV	0.15			
FW	0.48	0.30		
SH	0.67	0.36	0.70	
ER	0.52	0.33	0.73	0.84

† EV = safety-first index with variance across environment as stability parameter, FW = safety-first index with Finlay and Wilkinson's regression coefficient as stability parameter, SH = safety-first index with Shukla's stability variance as stability parameter, and ER = safety-first index with Finlay and Wilkinson's regression coefficient and Eberhart and Russell's deviation mean square as stability parameters.

strongly affected by the across-environment variance in addition to the mean yield. The mean ranking is somewhat correlated (rank correlation > 0.45) with the rankings from FW, SH, and ER, probably because the stability statistics influencing the rankings of FW, SH, and ER are considerably smaller than the across-environment variance in the EV index. A smaller stability statistic in a safety-first index produces rankings closer to the mean ranking.

There were a few large changes in rankings produced by the various methods. The experimental variety Ferke(1) was ranked first based on the mean, SH, and ER indices, second based on FW, and fifth based on EV. Pirsabak(1) was ranked last by the mean, FW, SH, and ER, but was ranked fourth by EV. This reversal may have been due to early maturity, which would lower yield but also produce smaller across-environment variance. Ikenne(1) was ranked near the top by the mean, EV, SH, and ER, but was ranked seventh by FW since its b_i differed substantially from 1. All indices ranked Kolhapur, also from the same early population as Pirsabak(1), near the bottom.

DISCUSSION

The different safety-first selection indices gave different rankings for the entries from the CIMMYT experimental variety trial. Rank changes occurred because entry rankings can be quite sensitive to the specified level of α and to the chosen definition of stability. An α of 0.05 was used in this example to illustrate how serious concerns with low yields can affect entry rankings. However, other values of α may be justified. Ideally, the plant breeder would determine the average value of α from the farmers for whom the breeding program is targeted. If direct elicitation is not possible, previous research may be useful in obtaining an estimate of α. For example, subsistence farmers' risk preferences have generally been shown to have $Z(1-\alpha)$ values between 0.5 and 1.5; assuming normality of yield, this approximately translates to values of α between 0.30 and 0.05 (Dillon and Scandizzo, 1978; Hazell, 1982).

The choice of a particular definition of stability also has a major impact on entry rankings (see Lin et al., 1986, for definitions of the types of stability). Type 1 stability (S_i^2) depends on the diversity of environments in the experiments. If environments are quite diverse, such as a set of sites from a continental area, then Type 1 stability, and thus the EV index, may not be very meaningful. However, if the range of environments could be restricted, then Type 1 stability and the EV index might be useful.

Type 2 stability ($\bar{b}_i$ and $\hat{\sigma}_i^2$) considers a cultivar stable if its response to environment is parallel to the average response of all cultivars 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 that depends on the cultivars in the trial, and thus statements based on this type of stability must be restricted to only those cultivars being tested. Consequently, the FW and SH indices may be useful for evaluating a given set of cultivars relative to one another over a broad range of environments, but extreme care should be exercised when using these indices to make inferences about cultivars not in the test.

Type 3 stability ($S_{\delta i}^2$) ideally measures unpredicatable irregularities of a cultivar'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 cultivars 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 severely criticized (Lin et al., 1986). If the environmental index in ER could be replaced by actual environmental factors such as temperature or rainfall, the ER would clearly be the preferred safety-first index of those presented.

There appear to be several advantages to using a safety-first index. The safety-first approach is based on the reasonable assumption that the plant breeder is primarily concerned with avoiding disaster by choosing cultivars which have little chance of producing poor yields. Also, the safety-first index has intuitive appeal in that it is simply a lower confidence bound. In addition, a safety-first index explicitly weighs the importance of stability relative to yield. Finally, the safety-first approach may be used with all three types of univariate stability statistics as defined by Lin et al. (1986) and can be used with any type of index in place of yield alone.

Nevertheless, several disadvantages may limit the applicability of the proposed safety-first selection indices. Specifying a realistic value of α may be a formidable task, especially if the target farmers must be surveyed. Also, the indices are based on estimated variances, which can have very large standard errors even with a moderate number of environments. Imprecise variance estimates may produce cultivar rankings of questionable value. Finally, alternative safety-first indices can be developed (see for example Roy, 1952, and Telser, 1955).

APPENDIX

Derivation of Eq. [1] based on Kataoka (1963).

Assume Y_{ij} is the yield of the ith cultivar in the jth environment which has a normal distribution with population mean μ_i and variance σ_i^2 over all environments. If the breeder follows Kataoka's safety-first approach, the breeder will choose the cultivar with the largest lower confidence limit d_i subject to the condition $P(Y_{ij} \leq d_i) = \alpha$. Because Y_{ij} is normally distributed

$$P(Y_{ij} \leq d_i) = P([Y_{ij} - \mu_i]/\sigma_i \leq [d_i - \mu_i]/\sigma_i) = F([d_i - \mu_i]/\sigma_i) = \alpha$$

where $F(\cdot)$ is the standard normal cumulative distribution function. Then,

$$[d_i - \mu_i]/\sigma_i = F^{-1}(\alpha) \quad [1a]$$

where $F^{-1}(\alpha) = -Z(1 - \alpha)$, which is the $1 - \alpha$ percentile from the standard normal distribution when $\alpha < 0.5$. Using $-Z(1 - \alpha)$ and rearranging Eq. [1a] gives

$$d_i = \mu_i - Z(1 - \alpha)\sigma_i \quad [2a]$$

In practice, μ_i and σ_i are estimated with $\bar{Y}_{i.}$ and $(V_i)^{1/2}$ computed from the trial. Therefore, if the breeder follows Kataoka's approach, the cultivar with the largest value of $\bar{Y}_{i.} - Z(1 - \alpha)(V_i)^{1/2}$ will be preferred.

Finlay and Wilkinson's approach.

This method characterizes the value of a cultivar by its mean yield μ_i, and how far its regression coefficient (β_i) deviates from 1. To express this model in terms of a mean and variance which may be used in Eq. [1], note that the predicted yield values (Y^*_{ij}), contain all the useful information:

$$Y^*_{ij} = \mu_i + \beta_i(\bar{Y}_{.j} - \bar{Y}_{..})$$

where μ_i is the population mean yield of the ith cultivar, β_i is the population regression coefficient and $\bar{Y}_{.j}$ the marginal mean of environment j (which is assumed to be a random variable with true mean $\mu_{\bar{y}}$ and variance $\sigma_{\bar{y}}^2$). By adding and subtracting the product of the mean slope and the environment index, $\bar{\beta}(\bar{Y}_{.j} - \bar{Y}_{..})$, to the right side of this equation, we obtain:

$$Y^*_{ij} = \mu_i + \bar{\beta}(\bar{Y}_{.j} - \bar{Y}_{..}) + (\beta_i - \bar{\beta})(\bar{Y}_{.j} - \bar{Y}_{..}).$$

But $\bar{\beta}(\bar{Y}_{.j} - \bar{Y}_{..})$ contains no information about the ith cultivar, since it represents how the average cultivar responds to the environmental index. Therefore subtracting $\bar{\beta}(\bar{Y}_{.j} - \bar{Y}_{..})$ from both sides of the equation gives the following adjusted predicted yield (YA^*_{ij}), which contains all the useful information about the ith cultivar considered important by Finlay and Wilkinson's approach:

$$YA^*_{ij} = \mu_i + (\beta_i - \bar{\beta})(\bar{Y}_{.j} - \bar{Y}_{..}).$$

Since the mean slope ($\bar{\beta}$) is always 1, and using the rules of expectation and variance, the population mean and variance over environments of the adjusted predicted yield for the ith cultivar can be shown to be μ_i and $(\beta_i - 1)^2 \sigma_{\bar{y}}^2 (1 - 1/q)$, respectively.

Shukla's stability variance.

Following Shukla (1972), define the following model:

$$Y_{ij} = \mu + G_i + E_j + GE_{ij}$$

where μ is the grand mean, G_i is the fixed effect of cultivar i, and E_j and GE_{ij} are environment and GE interaction effects. The E_j and GE_{ij} are assumed to be normally and independently distributed with expectation 0, and variances σ_E^2 and σ_i^2, respectively. Then using rules of expectation and variance, and taking expectations over all environments for cultivar i, the population mean and variance of the yield of cultivar i are $\mu + G_i = \mu_i$ and $\sigma_E^2 + \sigma_i^2$, respectively.

Eberhart and Russell's approach.

This approach characterizes the desirability of a cultivar using three parameters: its mean yield (μ_i), Finlay and Wilkinson's regression coefficient (β_i), and the mean square deviations about regression ($\sigma_{\delta i}^2$). Following Eberhart and Russell (1966), define the following model:

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

where μ_i, β_i, and $\bar{Y}_{.j}$ are defined as in Finlay and Wilkinson's model and δ_{ij} is normally distributed error with mean 0, and variance $\sigma_{\delta i}^2$. As in the derivation of the FW index, adding and subtracting the product $\bar{\beta}(\bar{Y}_{.j} - \bar{Y}_{..})$ to the right side of this equation and then subtracting $\bar{\beta}(\bar{Y}_{.j} - \bar{Y}_{..})$ from both sides of the resulting equation gives the following adjusted yield (YA_{ij}), which contains all the information about the ith cultivar relevant to the Eberhart and Russell approach:

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

Using rules of expectation and variance and since the mean slope ($\bar{\beta}$) is always 1, the ith cultivar's population mean and variance across all environments can be shown to be μ_i and $(\beta_i - 1)^2 \sigma_{\bar{y}}^2 (1 - 1/q) + \sigma_{\delta i}^2$, respectively.

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