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Simultaneous Selection for High Yielding and Stable Crop Genotypes

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ABSTRACT

Integration of stability of performance with yield is essential in yield trials. Methods that select for high yield and stability have been developed, but have not been compared for their usefulness. Our objective was to compare these methods and to study their relationship to yield and the stability-variance statistic (σ_i^2). We compared Kang's (1988b) rank-sum method (Index 1; equal weights for yield and σ_i^2) and four additional rank-sum indices [two (Index 2), three (Index 3), four (Index 4), and five (Index 5) times more weight for yield than for stability variance] with Hühn's (1979) S_i^3 and S_i^6 statistics, and Lin and Binns' (1988) P_i. All statistics were calculated for each of five sets of data from international maize (*Zea mays* L.) yield trials. In Set 1, low σ_i^2's (indicative of stable performance) were generally associated with high yield ($r_s = 0.73$), but in Set 2 low σ_i^2's appeared to be associated with low yield ($r_s = -0.46$). Index 1 ranks were positively correlated with σ_i^2 ranks in Sets 2 to 5 as were S_i^3 ranks. Index 1 and S_i^3 offered an opportunity to select for both stability based on σ_i^2 and yield. Indices 2, 3, 4, and 5, and P_i favored selection primarily for yield. It was assumed that the top 50% genotypes would be selected, in Sets 1 and 2, on the basis of yield rank alone or individual statistics. In Set 1, Index 1 was slightly more conservative than S_i^3, in that Index 1 selected a higher yielding genotype from the two lowest yielding genotypes than did S_i^3. S_i^6 was slightly more conservative than Index 1. Index 1 was intermediate between S_i^3 and S_i^6. In Set 2, Index 1 and Index 2 were more conservative than S_i^3, whereas S_i^6 was more conservative than Index 1, but less conservative than Index 2. P_i favored selection for yield only. We concluded that Kang's rank-sum method (Index 1 here) and Hühn's S_i^3 and S_i^6 statistics would be useful for simultaneously selecting for yield and yield stability.

STABILITY OF PERFORMANCE should be considered an important aspect of yield trials. Genotype × environment (GE) interaction can reduce progress from selection. The methods of partitioning GE interaction into components assignable to each genotype, measure the contribution of each genotype to GE interaction. The useful methods that fall into this category are: ecovalence (W_i) developed by Wricke (1962) and the stability-variance statistic (Shukla, 1972).

Several stability statistics have been examined to study stability of genotypes with respect to an individual trait (Kang and Miller, 1984; Kang and Gorman, 1989; Lin et al., 1986; Pham and Kang, 1988). Integration of stability of performance with yield is necessary for selecting high-yielding, stable genotypes. In general, practical application of stability statistics to yield trials has not been done. Both yield and stability of performance should be considered simultaneously, to reduce the effect of genotype × environment interaction and to make selection of genotypes more precise and refined. A few methods that simultaneously estimate yield and stability have been proposed. Stability statistics that consider deviations from a hypothetical, desired genotype (Sepahi, 1974) are associated primarily with yield level and show little correlation with stability (Léon, 1986). Therefore, they are not suitable for simultaneous selection of yield and stability.

The concept of risk aversion was adapted by Barah et al. (1981). They indicated that only the stability component was relevant for farmers in their adoption decision. They used measures of farmer's risk aversion to rank genotypes according to preferences that took account of both yield and stability. They found no significant differences between yield-based rankings and rankings obtained from both yield and stability. Eskridge (1990) recently advocated the use of a decision theory concept, known as safety-first, to develop an index that incorporates mean yield and stability. He indicated that safety-first selection indices can be useful to plant breeders when the genotype × environment interaction is large, and poor yield results in severe consequences such as bankruptcy or starvation.

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Hühn (1979) proposed two non-parametric statistics that combine yield and stability. These statistics (S_i^3 and S_i^6) based on yield ranks of genotypes in each environment, are expressed as follows:

$$S_i^3 = \frac{\sum_j (r_{ij} - \bar{r}_{i.})^2}{\bar{r}_{i.}}$$

$$S_i^6 = \frac{\sum_j | r_{ij} - \bar{r}_{i.}|}{\bar{r}_{i.}}$$

where r_{ij} is the rank of ith genotype in jth environment and $\bar{r}_{i.}$ is the mean of ranks over all environments for ith genotype.

Both S_i^3 and S_i^6 showed significant correlation with yield and stability statistics W_i (ecovalance) and sd_i^2 (deviation from regression) (Léon, 1986). S_i^6 is more strongly correlated with grain yield and less with stability statistics than S_i^3. A choice between S_i^3 and S_i^6 gives the opportunity to weight yield or yield stability (Léon, 1986). These statistics have been reviewed by Becker and Léon (1988). Practical use of these statistics has not been reported.

Kang (1988b) developed a method for selecting high yielding, stable genotypes. Ranks were assigned for mean yield with the genotype with the highest yield receiving the rank of 1. Similarly, ranks were assigned for the stability-variance (σ_i^2) of Shukla (1972), with the lowest estimated value receiving the rank of 1. The two ranks for each genotype were summed and the lowest rank-sum was regarded as most desirable. This method (Index 1) assumed equal weight for yield and stability variance. However, plant breeders may prefer to assign more weight to yield than to stability variance. In addition to assigning equal weight to yield and the stability-variance statistic, we are considering assigning two (Index 2), three (Index 3), four (Index 4), and five (Index 5) times more weight to yield than to the stability-variance statistic.

Lin and Binns (1988) developed a superiority measure of the ith test cultivar (P_i) for cultivar × location data. The P_i was defined as the distance mean square between the cultivar's response and the maximum response averaged over all locations, and is expressed as follows:

$$P_i = \sum_{j=1}^{n} (X_{ij} - M_j)^2/_{2n}$$

where X_{ij} is the yield of the ith cultivar grown in the jth location, M_j is the maximum response among all cultivars in the jth location, and n is the number of locations. Here, cultivar selection is based on P_i values. The smaller the P_i value, the better the cultivar. The P_i value represents superiority in the sense of general adaptability (Lin and Binns, 1988). Lin and Binns (1988) state, "If the selection is based solely on P_i, a narrowly adapted cultivar, i.e., poor in general adaptability but good in specific adaptability, may be discarded. This is avoided by computing a pairwise GE interaction mean square between the maximum response and each test cultivar. If the mean square is not substantially larger than the estimated error, it implies parallelism of both responses (i.e., the differences from the maximum responses are about the same for all locations). Under such circumstances, the P_i value is an appropriate indicator of superiority. On the other hand, a large GE interaction implies differences in the response patterns and comparison by P_i values becomes meaningless. Then, a breeder should examine the specific adaptability of that particular cultivar individually by plotting the observed values of both the maximum response and the candidate cultivar on the location mean. The closeness of the observed values of the candidate cultivar and the maximum response indicates areas of specific adaptability."

Lin and Binns' (1988) method appears to be very cumbersome because if one evaluates 100 cultivars in a test, 99 separate analyses of variance will have to be computed. Usefulness of this method has not been demonstrated. Although Lin and Binns (1988) have not stated this, their purpose appeared to be to integrate yield and stability.

The objective of this research is to study interrelationships between the five rank-sum indices, Hühn's (1979) S_i^3 and S_i^6 statistics, Lin and Binns' (1988) P_i via rank correlations in five international maize yield trials (Pham and Kang, 1988). In addition, usefulness of each method will be evaluated using data from two yield trials.

MATERIALS AND METHODS

Five sets of different experimental, open-pollinated cultivars (EC) of maize were evaluated in the international maize yield trials conducted by the International Center for the Improvement of Maize and Wheat (CIMMYT). Set 1 included 14 ECs grown in 1983 to 1984 at 39 locations in 21 countries; Set 2 included 23 ECs tested in 1983 to 1984 at 46 locations in 27 countries; Set 3 included 16 ECs evaluated in 1984 to 1985 at 23 locations in 13 countries; Set 4 included 18 ECs tested in 1984 to 1985 at 25 locations in 15 countries; and Set 5 included 12 ECs grown in 1984 to 1985 at 17 locations in 10 countries. Each set was evaluated in a randomized complete-block design with four replications per location.

A combined analysis of variance was calculated for each set. The EC × location interaction in each set was significant. The EC (genotype) mean yields over replications were calculated for each location in each trial. The σ_i^2 statistic was computed from genotype × location data using the BASIC program developed by Kang (1988a). Ranks were assigned for mean yield with the genotype having the highest yield receiving the rank of 1. Similarly, ranks were assigned for σ_i^2 with the lowest estimated value receiving the rank of 1. Index 1 was derived from the sum of yield rank and σ_i^2 rank (Kang, 1988b), Index 2 from the sum of 2(yield rank) and σ_i^2 rank, Index 3 from the sum of 3(yield rank) and σ_i^2 rank, Index 4 from the sum of 4(yield rank) and σ_i^2 rank, and Index 5 from the sum of 5(yield rank) and σ_i^2 rank.

Hühn's (1979) non-parametric statistics, S_i^3 and S_i^6, and Lin and Binns' (1988) P_i were calculated via computer programs developed by Kang (unpublished). The computer programs are written in the MATRIX programming language of SAS (1985) and are available, upon request, from M.S. Kang. The lowest value for S_i^3, S_i^6, and P_i was assigned the rank of 1. Rank-correlation coefficients were computed among σ_i^2, yield, indices 1-5, S_i^3, S_i^6, and P_i for the five sets.

RESULTS AND DISCUSSION

Rank-correlation coefficients among the stability variance statistic (σ_i^2), mean yield, rank-sum indices 1 to 5, Hühn's (1979) statistics S_i^3 and S_i^6, and P_i for the five sets are shown in Table 1. Rank-correlation coefficients between σ_i^2 and yield were significant for Set 1 (0.73) and Set 2 (−0.46), which indicated that in Set 1, low σ_i^2's were generally associated with high yield, but in Set 2, low σ_i^2's appeared to be associated with low yield (Table 1). Index 1 was associated with σ_i^2 in Sets 2 to 5 as was S_i^3. Indices 2, 3, 4, and 5, S_i^6, and P_i were not consistently rank-correlated with σ_i^2 in all sets. Index 1, S_i^3, and S_i^6 appeared to offer an opportunity to select for both stability based on σ_i^2 and yield. Indices 2, 3, 4, and 5, and P_i showed a high degree of relationship with yield; therefore, selection based on these methods would favor selection primarily for yield.

Mean genotype yield, σ_i^2, and rankings according to yield, five rank-sum indices, S_i^3, S_i^6, and P_i for Sets 1 and 2 are shown in Table 2 and Table 3, respectively. These two sets were selected because of their contrasting relationships between σ_i^2 and yield (Table 1). Suppose that the top 50% genotypes in Set 1 are selected (Table 2). These selections based on yield alone have yield ranks of 1 to 7. When selection is made on the basis of Index 1, i.e., equal weights for yield and stability variance, the top seven selections would be those having the yield ranks of 4, 3, 1, 9, 10, 13, and 5. Yield rank 7 also would be selected because of its tie with yield rank 5 and about equal yield. When Index 2 is used, i.e., yield with twice the weight of stability variance, the top seven selections would be those having the yield ranks of 4, 1, 3, 2, 5, 7, and 6. If Index 3 is used, seven genotypes with the yield ranks of 1, 3, 4, 2, 5, 6, and 7 would be selected. These are the same seven genotypes selected on the basis of yield rank alone. Indices 2 to 5 and P_i selected the same seven cultivars as those selected on the basis of yield rank alone. Therefore, these five methods were not useful for concurrently selecting for yield and stability variance.

The statistic S_i^3 would select yield ranks 4, 9, 6, 3, 5, 14, and 1 (Table 2). Index 1 and S_i^3 selected the same five genotypes, i.e., yield ranks 1, 3, 4, 5, and 9. Index 1 selected yield ranks 10 and 13 instead of yield ranks 6 and 14. Index 1 appeared to be slightly more conservative than S_i^3, i.e., Index 1 selected a higher yielding genotype (yield rank 13 instead of 14) from

Table 1. Rank-correlation coefficients (r_s) among stability-variance (σ_i^2), yield, and several simultaneous selection for yield and stability statistics (five rank-sum indices, Hühn's nonparametric statistics S_i^3 and S_i^6, and Lin and Binns' P_i) for five sets.†

			Index (I)							
		Yield	1	2	3	4	5	S_i^3	S_i^6	P_i
	Set	r_s								
σ_i^2	1	0.73**	0.30	−0.49	−0.66**	−0.73**	−0.79**	−0.02	−0.39	−0.71**
	2	−0.46*	0.69**	0.48*	0.36	0.23	0.17	0.50*	0.31	0.11
	3	0.02	0.64**	0.31	0.24	0.13	0.08	0.78**	0.58*	0.27
	4	0.03	0.67**	0.43	0.31	0.22	0.19	0.70**	0.37	0.13
	5	−0.02	0.58*	0.24	0.10	0.03	−0.04	0.72**	0.27	−0.15
Yield	1		−0.26	−0.89**	−0.96**	−0.98**	−0.99**	−0.28	−0.62*	−0.97**
	2		−0.72**	−0.88**	−0.93**	−0.97**	−0.98**	−0.79**	−0.92**	−0.99**
	3		−0.68**	−0.91**	−0.93**	−0.96**	−0.98**	−0.37	−0.64**	−0.90**
	4		−0.73**	−0.90**	−0.95**	−0.97**	−0.97**	−0.57*	−0.87**	−0.96**
	5		−0.65*	−0.89**	−0.95**	−0.97**	−0.99**	−0.34	−0.77**	−1.00**
I 1	1			0.62*	0.48	0.39	0.32	0.42	0.37	0.43
	2			0.95**	0.90**	0.83**	0.79**	0.90**	0.84**	0.75**
	3			0.91**	0.86**	0.79**	0.76**	0.85**	0.91**	0.88**
	4			0.95**	0.89**	0.86**	0.84**	0.89**	0.89**	0.79**
	5			0.90**	0.83**	0.79**	0.74**	0.81**	0.83**	0.65*
I 2	1				0.97**	0.94**	0.91**	0.42	0.68**	0.94**
	2				0.98**	0.94**	0.92**	0.94**	0.95**	0.90**
	3				0.99**	0.96**	0.94**	0.65**	0.83**	0.97**
	4				0.98**	0.97**	0.96**	0.82**	0.96**	0.93**
	5				0.98**	0.96**	0.93**	0.60*	0.89**	0.89**
I 3	1					0.99**	0.98**	0.40	0.70**	0.98**
	2					0.98**	0.96**	0.91**	0.95**	0.94**
	3					0.98**	0.97**	0.61*	0.81**	0.96**
	4					0.99**	0.99**	0.74**	0.93**	0.96**
	5					0.99**	0.98**	0.50	0.84**	0.95**
I 4	1						0.99**	0.37	0.68**	0.98**
	2						0.99**	0.84**	0.93**	0.97**
	3						0.99**	0.53*	0.75**	0.94**
	4						1.00**	0.70**	0.92**	0.95**
	5						0.99**	0.46	0.82**	0.97**
I 5	1							0.33	0.65*	0.98**
	2							0.83**	0.93**	0.98**
	3							0.47	0.70**	0.93**
	4							0.67**	0.91**	0.96**
	5							0.41	0.80**	0.99**
S_i^3	1								0.78**	0.36
	2								0.94**	0.82**
	3								0.92**	0.64**
	4								0.85**	0.64**
	5								0.62*	0.34
S_i^6	1									0.64*
	2									0.93**
	3									0.79**
	4									0.89**
	5									0.77**

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

† N = 14, 23, 16, 18, and 12 for Sets 1, 2, 3, 4, and 5, respectively.

Table 2. Mean yield, stability variance (σ_i^2), rankings and selection according to yield and several simultaneous selection for yield and stability statistics (five rank-sum indices†, S_i^3, S_i^6, and P_i) for Set 1.

Genotype	Yield	σ_i^2	Yield rank	Rank sum Index 1	Index 2	Index 3	Index 4	Index 5	S_i^3	S_i^6	P_i
	Mg ha^{-1}										
Santa Rosa 8073	4.85	0.9642	1(S)‡	14(S)	15(S)	16(S)	17(S)	18(S)	78.4(S)	15.7(S)	0.264(S)
Ilonga 8043	4.80	1.0458	2(S)	16	18(S)	20(S)	22(S)	24(S)	88.9	18.6	0.286(S)
Ferke 8129	4.79	0.5794	3(S)	12(S)	15(S)	18(S)	21(S)	24(S)	67.5(S)	15.9(S)	0.280(S)
Across 7622 RE	4.74	0.5204	4(S)	10(S)	14(S)	18(S)	22(S)	26(S)	55.3(S)	12.9(S)	0.291(S)
Gandajika 8022	4.72	0.6029	5(S)	15(S)	20(S)	25(S)	30(S)	35(S)	67.9(S)	15.6(S)	0.331(S)
Poza Rica 8129	4.72	0.6103	6(S)	17	23(S)	29(S)	35(S)	41(S)	66.0(S)	15.0(S)	0.346(S)
Kwadaso 8043	4.70	0.5694	7(S)	15(S)	22(S)	29(S)	36(S)	43(S)	80.6	17.5	0.337(S)
Ferke (1) 8129	4.69	0.7037	8	20	28	36	44	52	79.1	17.1(S)	0.368
Across 7729 RE	4.68	0.5185	9	14(S)	23	32	41	50	65.0(S)	14.9(S)	0.359
Rattray-Arnold (1) 8122	4.60	0.4570	10	14(S)	24	34	44	54	84.8	18.8	0.405
Across 8121	4.58	0.5364	11	18	29	40	51	62	96.6	20.3	0.457
Poza Rica 8121	4.58	0.4358	12	15	27	39	51	63	82.4	18.5	0.437
Jardinopolis 8121	4.57	0.3682	13	14(S)	27	40	53	66	79.9	19.0	0.422
Omonita (1) 8121	4.33	0.3780	14	16	30	44	58	72	76.6(S)	23.6	0.673

† Index 1 based on yield rank + σ_i^2 rank, Index 2 based on 2 (yield rank) + σ_i^2 rank, Index 3 based on 3 (yield rank) + σ_i^2 rank, Index 4 based on 4 (yield rank) + σ_i^2 rank, and Index 5 based on 5 (yield rank) + σ_i^2 rank.

‡ S = selected genotype.

the lowest two genotypes than did S_i^3. The term more conservative means that higher yielding genotypes are selected and vice verse.

The statistic S_i^6 selected yield ranks 4, 9, 6, 5, 1, 3, and 8 (Table 2). Index 1 selected yield ranks 10 and 13 instead of 6 and 8. Therefore, S_i^6 was slightly more conservative than Index 1.

The statistic S_i^3 appeared to give more weight to stability than did S_i^6. This was clear from the above comparison and also from rank correlations of S_i^3 and S_i^6 with yield (Table 1).

In Set 2 (Table 3), Index 1 selected the yield ranks 6, 2, 7, 11, 3, 5, 8, 1, 4, 19, 20 and 9. This index identified two genotypes from the bottom 50% of yield ranks, i.e., yield ranks 19 and 20. All other genotypes were from the top 50% yield ranks. Application of Index 2 allowed selection of yield ranks 2, 6, 3, 7, 1, 5, 4, 8, 11, 9, 13 and 10. Each of these yield ranks was in the top 50% with the exception of yield rank 13. The yield rank order for Index 2 is much different from that given by yield alone. Index 3 allowed selection of yield ranks 2, 1, 6, 3, 5, 7, 4, 8, 11, 9, 10, and 13. This index was similar to Index 2 in identifying the top 50% selections. Index 4 selected the yield ranks 2, 1, 3, 6, 4, 5, 7, 8, 11, 9, 10, and 13, which are similar to those of Index 2 and Index 3, but with the yield rank order closer to that of yield alone. Yield ranks using Index 5 were similar to those using Index 4.

In Set 2 (Table 3), S_i^3 would select yield ranks 2, 6, 3, 7, 1, 9, 5, 11, 13, 8, 20, and 10. Index 1 and S_i^3

Table 3. Mean yield, stability variance (σ_i^2), rankings and selection according to yield and several simultaneous selection for yield and stability statistics (five rank-sum indices†, S_i^3, S_i^6, and P_i) for Set 2.

Genotype	Yield	σ_i^2	Yield rank	Rank sum Index 1	Index 2	Index 3	Index 4	Index 5	S_i^3	S_i^6	P_i
	Mg ha^{-1}										
Guarare (1) 8128	4.55	0.6255	1(S)‡	19(S)	20(S)	21(S)	22(S)	23(S)	106.5(S)	13.7(S)	0.140(S)
Ferke (1) 8128	4.44	0.4394	2(S)	10(S)	12(S)	14(S)	16(S)	18(S)	80.4(S)	12.8(S)	0.183(S)
Guarare 8128	4.44	0.4755	3(S)	16(S)	19(S)	22(S)	25(S)	28(S)	91.4(S)	13.9(S)	0.182(S)
La Molina 8128	4.36	0.5654	4(S)	19(S)	23(S)	27(S)	31(S)	35(S)	122.0	17.2(S)	0.238(S)
Los Banos (1) 8136	4.36	0.4569	5(S)	16(S)	21(S)	26(S)	31(S)	36(S)	110.3(S)	16.2(S)	0.208(S)
Muneng 8128	4.36	0.3422	6(S)	9(S)	15(S)	21(S)	27(S)	33(S)	82.7(S)	13.7(S)	0.224(S)
La Molina (2) 8128	4.34	0.3629	7(S)	12(S)	19(S)	26(S)	33(S)	40(S)	93.2(S)	14.2(S)	0.237(S)
Across 8128	4.33	0.4438	8(S)	17(S)	25(S)	33(S)	41(S)	49(S)	113.3(S)	16.5(S)	0.240(S)
Poza Rica 8136	4.32	0.5182	9(S)	23(S)	32(S)	41(S)	50(S)	59(S)	109.4(S)	16.8(S)	0.259(S)
Ferke 8128	4.29	0.5859	10(S)	27	37(S)	47(S)	57(S)	67(S)	118.7(S)	17.4(S)	0.265(S)
La Molina (1) 8128	4.28	0.3426	11(S)	15(S)	26(S)	37(S)	48(S)	59(S)	111.0(S)	17.3(S)	0.275(S)
Los Banos 8027	4.28	0.6627	12(S)	32	44	56	68	80	125.2	17.4	0.308
Los Banos 8136	4.28	0.4487	13	23	36(S)	49(S)	62(S)	75(S)	111.5(S)	16.5(S)	0.277(S)
Suwan 8128	4.26	0.8059	14	35	49	63	77	91	187.2	23.7	0.315
Londrina 8136	4.24	0.6368	15	34	49	64	79	94	168.9	21.7	0.340
Across 7728 RE	4.20	0.5707	16	32	48	64	80	96	131.5	18.8	0.371
Across 8027	4.15	0.4593	17	29	46	63	80	97	135.0	19.7	0.367
Across 8024	4.12	0.3805	18	24	42	60	78	96	136.7	21.7	0.381
Iboperenda 8027	4.07	0.2546	19	20(S)	39	58	77	96	119.0	20.1	0.421
Iboperenda 8024	3.97	0.2955	20	22(S)	42	62	82	102	115.5(S)	20.5	0.528
Across 7627 RE	3.84	0.3980	21	28	49	70	91	112	162.6	28.2	0.657
Pichilingue (1) 7827	3.53	0.8556	22	44	66	88	110	132	180.5	36.7	1.126
Pichilingue (1) 7824	3.46	1.0592	23	46	69	92	115	138	180.9	35.9	1.223

† Index 1 based on yield rank + σ_i^2 rank, Index 2 based on 2 (yield rank) + σ_i^2 rank, Index 3 based on 3 (yield rank) + σ_i^2 rank, Index 4 based on 4 (yield rank) + σ_i^2 rank, and Index 5 based on 5 (yield rank) + σ_i^2 rank.

‡ S = selected genotype.

selected the same 10 genotypes, i.e., yield ranks 1, 2, 3, 5, 6, 7, 8, 9, 11, and 20. Index 1 selected yield ranks 4 and 19 instead of 10 and 13. Index 2 and S_i^3 selected the same 11 genotypes, i.e., yield ranks 1, 2, 3, 5, 6, 7, 8, 9, 10, 11, and 13. Index 2 selected yield rank 4 instead of 20. Indices 1 and 2 appeared to be more conservative than S_i^3 in that the indices 1 and 2 selected higher yielding genotypes than did S_i^3.

The S_i^6 would select yield ranks 2, 1, 6, 3, 7, 5, 8, 13, 9, 4, 11, and 13 (Table 3). Index 1 would select yield ranks 19 and 20 instead of 10 and 13. Indices 2, 3, 4, and 5, S_i^6, and P_i would select the same yield ranks. S_i^6 was more conservative than Index 1.

In Set 2, again S_i^3 appeared to give more weight to stability variance than did S_i^6. S_i^3 was more related to σ_i^2 than was S_i^6 (Table 1). Léon (1986) showed similar correlations between S_i^3 and W_i, and S_i^6 and W_i from winter wheat (*Triticum aestivum* L.) trials. The S_i^3 was significantly rank-correlated with S_i^6 (Table 1). The lowest correlation between the two statistics was 0.62 (set 5) and the highest correlation was 0.94 (set 2).

The S_i^6 was found to be a better predictor of yield ranks than S_i^3 (Table 1). Léon (1986) also indicated that S_i^6 showed a stronger correlation with yield and a lower correlation with stability than did S_i^3.

Index 1 and Index 2 were more conservative than S_i^3; whereas, S_i^6 was more conservative than Index 1, but less conservative than Index 2. Therefore, Index 1, being intermediate between S_i^3 and S_i^6, may well be a compromise. Index 1, proposed by Kang (1988b), assigns equal weight to yield and stability variance. Index 3, Index 4, and Index 5 produced almost identical rankings to those of yield alone (Table 1); therefore, these indices did not offer an opportunity to select for both yield and yield stability. P_i did not offer any advantage over other methods examined here. We concluded that Kang's (1988) rank-sum method (Index 1) and Hühn's (1979) S_i^3 and S_i^6 statistics would be useful tools for selecting simultaneously for yield and yield stability.

The W_i and σ_i^2 rank genotypes identically (Wricke and Weber, 1980; Kang et al., 1987); their statistical relationship has been elucidated by Kang et al. (1987). Therefore, rank-sum indices can be obtained from W_i or σ_i^2. Both parameters would be equally effective in determining the chosen index. The statistics σ_i^2 and sd_i^2 (deviation from regression) were found to be highly rank-correlated ($r_s > 0.91$) (Pham and Kang, 1988). Therefore, sd_i^2 also could be used to develop Index 1. However, σ_i^2 was not well correlated with b_i-ER or b_i-Sh (Pham and Kang, 1988). Therefore, b_i-ER and b_i-Sh were not considered as good stability statistics. Index 1 or some other indices can, however, be developed using s_i^2 (Shukla, 1972). The statistic s_i^2 is calculated from the residual GE variance following removal of heterogeneity from the total GE variance.

The number of environments used to calculate σ_i^2 must be adequate. The greater the number of environments, the more reliable the estimated stability statistics. The minimum number of environments in this study was 17 for Set 5 and the maximum number was 46 for Set 2. For these statistics to be used effectively in rank-sum indices, the minimum number of environments should not be less than 10 as the precision with which the stability statistics are calculated would be reduced with fewer environments.

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