

Potential gain from selection for yield stability in two grain sorghum populations*

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Summary. Maximum yield under highly unpredictable environments should be associated with selection of genotypes with superior performance across good and poor environments. Several stability parameters have been proposed to identify superior genotypes over a wide range of environments. None of these has been used as selection criteria, however, because of their low heritability. The objective of the study presented here was to compare the relative efficiency of predicted gain from indirect selection among three stability parameters: the coefficient of regression (b), deviation from regression (S_d^2), and principal components scores (PC) from the AMMI model; two indices including mean yield and a stability parameter; and three indices involving yield at the best, the worst, and an intermediate environment. Two hundred S_1 families from each of two sorghum populations (TP24D and KP9B) were evaluated at four dryland environments over 2 years. The low heritability estimates and the low genetic correlation between the various stability parameters and mean yield resulted in their low relative efficiency as indirect selection criteria for high yield across environments. However, when the parameters were combined with mean yield over all to create indices, the relative efficiency increased for all the environments. In terms of resource allocation, these indices were not as efficient as mean productivity, rank summation, and selection index that involved fewer environments in their estimation.

Key words: Sorghum – Indirect selection criteria – Yield stability

Introduction

Sorghum (*Sorghum bicolor* L. Moench) improvement has been limited in target areas with highly unpredictable environments. The main reason is the poor performance of genotypes of the great differences among environmental conditions. One of the major constraints to selection under these variable environments has been the significance of the genotype \times environment interaction, expressed as the relative changes in rank among the genotypes across environments.

Ceccarelli (1989) suggested two main approaches to selection when significant genotype \times environment interactions were present. The first involved selection for low genotype \times environment interactions and high mean yields. This approach identifies genotypes widely adapted to all but the most severe stress environments. The second approach is based on the use of genotype \times environment interactions ($G \times E$) by breeding for maximum yield and stability within specific macroenvironments. Becker and Leon (1988) concluded that the use of a dynamic measure of stability was better for selecting consistently high yielding genotypes with a more predictable response to the specific environments. The regression analysis method, which includes estimation of the coefficient of regression (b) and mean squares for the deviation from regression (S_d^2), has been the primary procedure used for characterization of stability in genotypes (Leon and Becker 1988).

Eskridge (1990) concluded that selection based on these stability parameters must include mean yield, yet none of these methods have clearly illustrated its use. He proposed a safety-first model based upon mean yield and a stability parameter. The safety-first model was used to make the final decision by choosing cultivars that have a small chance of producing poor yields.

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Zobel et al. (1988) proposed the additive main effects and multiplicative interaction (AMMI) model, which combined the additive analysis of genotypes and environments using the traditional analysis of variance (ANOVA) with the multiplicative analysis of the residuals using principal component analysis (PCA). The principal component (PC) scores for the variety and the environment could be considered estimates of the average $G \times E$ interaction. Based upon analysis of the residuals, they recommended this model as the best procedure for the analysis of stability of genotypes tested over environments.

Although many authors have recognized the importance of stability as a breeding objective, most have used these analyses only on a fixed set of varieties or hybrids to characterize their performance over test environments (Eberhart and Russell 1966; Scott 1967; Crossa et al. 1989). Stability has not been evaluated as a selection criteria either for a recurrent selection scheme or for early generation selection because of its low heritability (Eagles et al. 1977; Becker and Leon 1988) and poorer relationship to improved adaptation over a range of unpredictable environments (Wright 1976).

Normally, the estimation of stability has included performance of a genotype in a large number of environments; however, other options have been proposed when the primary objective is the improvement of yield. Rosielle and Hamblin (1981) suggested the use of selection for mean productivity (average yield in stress and nonstress environments) or tolerance (difference between yield at these two environments). Zavala-Garcia et al. (1992) compared the relative efficiency of these two parameters with selection indices as indirect selection criteria in relation to direct selection at each environment separately. The optimal efficiency across the environments in the target area was predicted using (1) estimates of mean productivity, (2) an index using ranks, and (3) a Smith (1936) – Hazel (1943) index that involved the best, worst, and an intermediate environments.

The objective of the study presented here was to compare the relative efficiency of predicted gain from indirect selection among three stability parameters, two selection indices that included a stability parameter and mean yield, and three indices (mean productivity, rank summation, and a selection index) developed in Zavala-Garcia et al. (1992).

Materials and methods

The experimental material included 200 S_1 families derived from each of the two sorghum populations, TP24D and KP9B. The TP24D population is an early maturity derivative of TP24 that was originally synthesized at Texas A & M University by F. R. Miller and then randomly mated and selected for improved grain yield at the University of Georgia (R. R. Duncan, personal communication). After three further random matings at Mead,

Neb. (J. D. Eastin, unpublished data), 200 S_1 families were randomly derived. The KP9B population was synthesized from a cross of IAP2B genetic male steriles with 22 elite inbreds. The crosses were bulked and randomly mated with another population, YE Kafir. The bulk was randomly mated once under severe water and heat stress and twice under moderate stress. The 200 S_1 families were derived at random from half-sibs in 1986.

The 400 S_1 families were evaluated in a replications-in-block design; eight blocks of 25 families were grown in two replications for each population at four locations in 1987 and 1988. The four locations were Mead, Neb., and Hesston, Garden City, and Parsons, Kan.

The soil types were a Sharpsburg silty clay loam at Mead; a Ladysmith fine montmorillonitic mesic pachic arqustolls at Hesston; a Manter fine sandy loam at Garden City; and a Parsons fine mixed thermic mollic albaqualfs at Parsons. The plots at Mead received 500 and 340 mm of precipitation; Hesston received 460 and 470 mm; Garden City received 150 and 130 mm; and Parsons 320 and 530 mm in 1987 and 1988, respectively. The growing degree days (GDD), determined by subtracting the base temperature (10 °C in sorghum) from the daily average temperature, were 1464 and 1675 for Mead, 1693 and 1753 for Hesston, 1628 and 1536 for Garden City, and 2024 and 2068 for Parsons in 1987 and 1988, respectively.

The experiments were planted on 4 June 1987 and 27 May 1988 at Mead, 8 June 1987 and 7 June 1988 at Hesston, 2 June 1987 and 14 June 1988 at Garden City, and 15 May 1987 and 22 May 1988 at Parsons. Experimental plots consisted of one 6-m row with 0.75 m between rows. The fertilizer applied before planting was 110 kg ha⁻¹ of N applied at Mead in 1987 and 55 kg ha⁻¹ of N in 1988; Hesston and Garden City received 56 kg ha⁻¹ of N in both years; and 45 kg ha⁻¹ of N was applied at Parsons in both years. This last location received an additional 12 kg ha⁻¹ of P and 23 kg ha⁻¹ of K in both years. For weed control, 16.5 kg ha⁻¹ of 2-chloro-*N*-isopropylacetanilide and 5.5 kg ha⁻¹ of 2-chloro-4-(ethylamino)-6-(isopropylamino)-*S*-triazine were applied at Hesston, Garden City, and Parsons during both 1987 and 1988; Mead received 3.5 kg ha⁻¹ and 1.5 kg ha⁻¹ of the same products, respectively, in both years.

Twenty days after planting, the experiments were cultivated and thinned to final populations of 131,000 plants ha⁻¹ at Mead, Hesston, and Parsons, the population was 87,000 plants ha⁻¹ at Garden City. Grain yield was determined and adjusted to 140 g kg⁻¹ moisture.

The coefficient of regression (b) and mean squares for deviation from regression (S_a^2) stability parameters were calculated for each S_1 family based on the Eberhart and Russell (1966) model: $Y_{ij} = \mu_i + \beta_i I_j + \delta_{ij}$, where Y_{ij} was the variety mean of the i^{th} variety at the j^{th} environment, μ_i was the mean of the i^{th} variety across all environments, β_i was the coefficient of regression of the i^{th} variety, I_j was the environmental index calculated as the mean of all varieties at the j^{th} environment minus the grand mean, and δ_{ij} was the deviation from regression of the i^{th} variety at the j^{th} environment. The analysis was performed on the mean of each variety at each environment and each replication separately.

Stability also was estimated using the scores from the principal component analysis (PCA) on the residuals. The additive main effects and multiplicative interaction (AMMI) model was used:

$$Y_{ge} = \mu + \alpha g + \beta e + \sum_{n=1}^N \xi_n \xi_{gn} \phi_{en} + \Theta_{ge},$$

where Y_{ge} was the yield of g^{th} genotype in the e^{th} environment; μ was the grand mean; αg was the genotype mean deviation; βe was the environmental mean deviation; ξ_n was the eigenvalue of the PCA axis; ξ_{gn} , and ϕ_{en} were the genotype and environment PCA scores for the PCA axis, n ; N was the number of PCA

axes retained in the model, and θ_{ge} was the residual (Zobel et al. 1988).

The raw data were standardized for the block effect with a block mean equal to 0 and block standard deviation equal to 1. The AMMI model was used separately for each population on the means of each family at each environment and each replication. The PC scores from these analyses were used to estimate components of variance using the replication-in-block design.

Smith (1936) – Hazel (1943) selection indices were calculated using the coefficient of regression (b), the principal component scores (PC), and mean yield in various combinations. The selection indices included the coefficient of regression (b) and mean yield (SIBYLD) and principal component (PC) scores and mean yield (SIPCYLD) with economic weights of 1. The selection indices calculated were:

$$\text{SIBYLD} = 0.34 b + 0.98 \text{ mean yield overall in TP24D}$$

$\text{SIBYLD} = 0.28 b + 0.80 \text{ mean yield overall in KP9B}$ for the indices that involved the coefficient of regression (b), and

$$\text{SIPCYLD} = 0.34 \text{ PC} + 0.87 \text{ mean yield overall in TP24D}$$

$\text{SIPCYLD} = 0.43 \text{ PC} + 0.92 \text{ mean yield overall in KP9B}$ for the indices that involved the PC scores from the AMMI model.

The other selection parameters calculated were mean productivity (MBIW) calculated as (yield in the best environment + yield in the intermediate environment + yield in the worst environment)/3; rank summation (RBIW) calculated as (rank in the best environment + rank in the intermediate environment + rank in the worst environment); and selection index (SIY) based upon environments that were chosen on the basis of the cluster analysis of the genetic correlations and heritability as described in Zavala-Garcia et al. (1992). The selection indices used were:

$$\begin{aligned} \text{SI (TP24D)} &= 0.41 \text{ Hesston 1988} + 0.53 \text{ Mead 1987} \\ &\quad + 0.21 \text{ Parsons 1987} + 0.20 \text{ overall mean, and} \\ \text{SI (KP9B)} &= 0.90 \text{ Mead 1987} + 0.71 \text{ Mead 1988} \\ &\quad + 0.66 \text{ Garden City 1988.} \end{aligned}$$

Heritability was estimated as per Jan-Orn et al. (1976): $h^2_{S_1} = \sigma^2_{G(S_1)} / \sigma^2_{P(S_1)}$, where $\sigma^2_{G(S_1)}$ was the genetic variance estimated from the variance among S_1 families assuming no dominance effects and $\sigma^2_{P(S_1)}$ was the phenotypic variance among S_1 families.

The predicted response to direct selection (R_x) was estimated as $R_x = i h x \sigma_A$ (Falconer 1989), where i was the selection intensity at the 10% level, $h x$ was the square root of the heritability, and σ_A was the square root of estimated additive genetic variance for the families at the selection environment, Y . The genetic variance $\sigma^2_{G(S_1)}$ was used as an estimate of σ^2_A . Correlated response to indirect selection (CR_x) was estimated as $CR_x = i h x \sigma_A r_{xy}$ (Falconer 1989), where i was the selection intensity at the 10% level, $h x$ was the square root of the heritability of the yield in the response environment X , σ_A was the square root of the estimated additive genetic variance for the families in the selection environment Y , and r_{xy} was the genetic correlation of the family's yield in the response environment X and the same family's yield in the selection environment Y .

The relative efficiency (RE) or merit of indirect selection relative to direct selection was expressed as:

$$\text{RE} = \frac{\text{predicted gain from indirect selection}}{\text{predicted gain from direct selection}} \times 100$$

(Falconer 1989). These relative efficiency estimates were biased by standard errors associated with the genetic variance estimates under the assumption of no epistasis and no dominance effects. The top 10% of the families was selected for the different indirect selection criteria and direct selection for each environment. The number of families in common were compared.

Table 1. Analysis of variance for grain yield using the linear regression model and the additive main effects and multiplicative interaction (AMMI) model in 200 S_1 families from the TP24D and KP9B sorghum populations

Source of variation	df	Mean squares TP24D	Mean squares KP9B
<i>Linear regression model</i>			
Genotypes	199	4,746,053.97**	4,285,636.50**
Environments	7	500,877,769.40	378,330,165.10
Gen. \times Env.	1393	1,655,666.15	1,253,526.89**
Env. (linear)	1	3,554,650,655.0**	2,648,255,491.0**
Gen. \times Env. (linear)	199	1,146,564.4	1,340,672.5**
Pooled dev.	1200	1,691,391.9**	1,232,854.0**
Pooled error	1592	1,133,038.85	796,077.18
<i>AMMI model</i>			
Genotypes	199	3.37050**	3.84124**
Environments	7	0.01759	0.00000
Gen. \times Env.	1393	0.84018	0.84696**
PCA 1	205	1.27275**	1.34939**
Residual	1188	0.76554	0.76026
Error	1592	0.81164	0.74592
Total	3199	0.94832	0.98030

*** Significant at $P = 0.05$ and $P = 0.1$, respectively

Results and discussion

The total genotype \times environment ($G \times E$) variance for both the linear regression and the AMMI model was significant ($P \leq 0.01$) only for KP9B (Table 1). Because both models use the same additive model, this was expected. Further analysis of the linear regression model found that the three sources of variation in the total $G \times E$ variance were significant for KP9B but not significant for the genotype \times environment (linear) in TP24D. Thus, the coefficients of regression (b) were more homogeneous in the TP24D population. Further analysis of the interaction using principal component analysis (PCA) found that only one principal component was significant for both populations. The first component accounted for the majority of the $G \times E$ interaction variance, though the interaction was only significant for KP9B.

The heritability estimates for b, S^2_a , and PC were low and very similar in the two populations (Table 2). Becker and Leon (1988) reported similar heritability values for b (0.27–0.52). Eagles et al. (1977) also reported low values for b, but a high genetic correlation between b and yield. Thus, they concluded selection using yield would only identify genotypes with superior performance over all types of environments.

Significant genetic correlations were found for TP24D between b and mean yield in all the environments (defined base on the mean yield over the 200 families) except the poorest environment (Garden City 1988),

Table 2. Genetic correlations (r_g) between mean yield estimated from eight environments (Mead, Neb., and Hesston, Garden City, and Parsons, Kan., during 1987 and 1988) and the overall mean with the stability parameters, regression coefficient (b), deviation of regression (S_d^2), and principal component (PC) scores; genetic correlations between the stability parameters; and heritability for grain yield at the eight environments and for the stability parameters in TP24D and KP9B sorghum populations

Location	Mean kg ha ⁻¹	h ²	Parameter		
			b	S ² _d	PC
			r _g	r _g	r _g
<i>TP24D</i>					
b		0.31	1.00	0.02	0.37
S ²		0.40	0.02	1.00	0.09
PC ^d		0.32	0.37	0.09	1.00
Mead 1987	4580	0.69	0.92**	0.18	0.69**
Mead 1988	4220	0.61	0.76**	0.32*	0.24
Hesston 1987	2676	0.51	0.57**	0.01	0.52**
Hesston 1988	4154	0.57	0.58**	-0.03	-0.30**
Garden City 1987	3035	0.37	0.97**	0.17	0.51**
Garden City 1988	1221	0.37	0.18	0.21	-0.38**
Parsons 1987	4103	0.35	0.61**	0.29**	0.33**
Parsons 1988	2909	0.32	0.27*	0.15	0.56**
Overall mean	3362	0.15	0.81**	0.16	0.36**
<i>KP9B</i>					
b		0.25	1.00	0.05	0.54
S ²		0.48	0.05	1.00	0.85
PC ^d		0.39	0.54	0.85	1.00
Mead 1987	4558	0.63	0.06	-0.07	-0.27*
Mead 1988	4067	0.55	0.49**	0.69**	0.47**
Hesston 1987	2734	0.64	-0.15	0.15	0.17
Hesston 1988	3242	0.65	0.20	0.76**	0.64**
Garden City 1987	3024	0.45	0.18	0.12	0.46**
Garden City 1988	1754	0.53	-0.39**	0.06	-0.61**
Parsons 1987	4584	0.37	0.59**	0.24	0.38**
Parsons 1988	3797	0.43	0.41**	0.43**	0.65**
Overall mean	3470	0.20	0.20	0.39**	0.29*

*, ** Significant at $P = 0.05$ and $P = 0.1$, respectively

where the genetic correlation was only 0.18 (Table 2). These genetic correlation values at the different environments would indicate a cross-over response between this poor environment and the other intermediate to poor environments. The range of the b-values for KP9B was greater and more evenly distributed, and the genetic correlations between yield and b-values had a different pattern (Table 2). There was no relationship at the best environment (Mead 1987, $r = 0.06$), there was a negative relationship at the poorest environments (Hesston 1987, $r = -0.15$ and Garden City 1988, $r = -0.39$ **), and there were some positive significant correlations only in the intermediate environments. This indicated that more cross-overs occurred between genotype responses at the poorest and intermediate conditions and the best and intermediate conditions. The pattern of response for b in

KP9B was probably more curvilinear in this range of environments, unlike the very linear response of TP24D. Similar responses also could be found in the genetic correlations for mean squares of deviations from regression (S_d^2): a low genetic correlation with yield in each environment for TP24D and in all environments except Mead 1988, Hesston 1988, and Parsons 1988 for KP9B. Hill (1975) concluded that S_d^2 values could be affected by a non-linear regression model. Easton and Clements (1973) concluded that any departure from a linear regression could be associated more with "noise" factors; thus, S_d^2 was not considered as reliable as PC scores, an alternative measure of stability.

Genetic correlations between PC and mean yield were lower than the correlations between b and mean yield in TP24D in all eight environments and for the overall mean, except for Parsons 1988 (Table 2). The highest genetic correlation between PC and mean yield was in the best environment ($r = 0.69$, Mead 1987), whereas correlation was negative in the poorest environment ($r = -0.38$, Garden City 1988). In KP9B, on the other hand, the genetic correlations between PC and mean yield were higher than those between b and mean yield in all eight environments, except Parsons 1987. Both the best and poorest environment in this population had significant negative correlations ($r = -0.27$ for Mead 1987 and $r = -0.61$ for Garden City 1988). In general, the genetic correlations between PC and mean yield in comparison with the correlations between b and mean yield were different for each population.

Selection for b itself was a poor indirect selection criterion for higher yielding genotypes within the range of environments studied. Relative efficiencies of predicted gain from indirect selection for higher b-values were less than direct selection for yield at each environment in TP24D and KP9B because of the low heritability values of b and the low genetic correlation of b with yield, especially in the poorest environments. This suggests that high b values will select genotypes with low yield capabilities under severe stress conditions. Blum (1988) concluded that selection for high yielding genotypes under stress environments based on b values close to 0 will be at the expense of yield response under good environments. Thus, if the target area included nonstress and severe stress environments, the highest yielding genotypes under severe stress conditions would not be selected under optimal conditions, and vice versa. An important component required for success in selecting for both stress and non-stress environments, therefore, is acceptance of the fact that good performance under stress conditions and maximum yield potential under optimal conditions may be mutually exclusive concepts (Ceccarelli 1989).

Relative efficiencies of predicted gain from indirect selection for high PC values were low and negative in relation to direct selection for yield. Overall, the relative

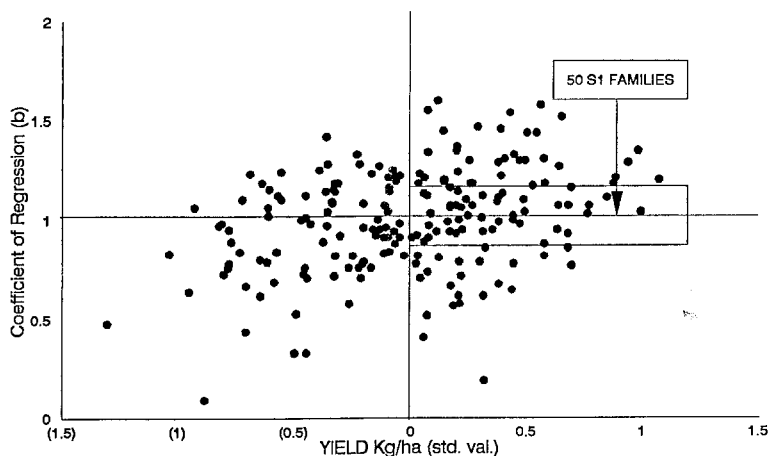


Fig. 1. S_1 families selected by independent culling using coefficient of regression (b) close to 1 and mean yield above the average in TP24D sorghum population

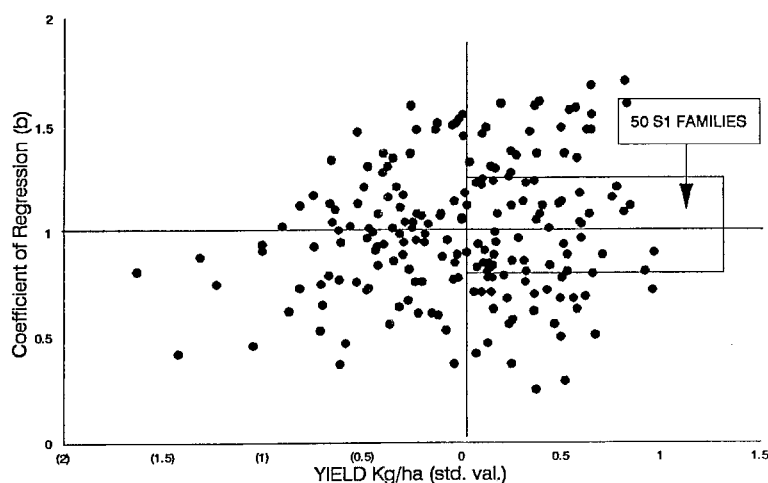


Fig. 2. S_1 families selected by independent culling using coefficient of regression (b) close to 1 and mean yield above the average in KP9B sorghum population

efficiency at each environment was similar to or lower than that of b -values, except in Parsons 1988 in TP24D. Similar results for both b -values and PC were found in KP9B, except for a slightly higher efficiency in Hesston 1988 and Garden City 1987. However, for KP9B, both the best environment and the poorest environment had negative relative efficiencies (Mead 1987 with -21% and Garden City 1988 with -53%). The predicted gain from indirect selection either for high b or for high PC values would not identify high yielding genotypes for good and stress environments and would have a negative effect on selection under stress environments.

Although we have been considering selection for higher values of b as a measure of responsiveness and PC as a stability parameter, Eberhart and Russell (1966) indicated that a stable genotype is defined as having a b value close to 1 and a low S_d^2 . Finlay and Wilkinson (1963), Eberhart and Russell (1966), and Shukla (1972) suggested that yield and a stability parameter were needed to increase the efficiency of selection when significant genotype \times environment interaction was present. To identify such genotypes in these two populations, we used independent culling selection with b values close to 1 and

mean yield above average (Figs. 1 and 2 for TP24D and KP9B, respectively) or PC scores close to 0 and mean yield above the average (Figs. 3 and 4 for TP24D and KP9B, respectively). We selected 50 families. The b -values for these 50 families ranged from 0.78 to 1.15 in TP24D and 0.79 to 1.25 in KP9B, and the PC scores ranged from -0.15 to 0.12 in TP24D and -0.14 to 0.19 in KP9B.

Selection from independent culling was compared with direct selection at each environment separately. On the basis of the number of families in common in the top 10% of the highest yielding genotypes at each environment and the 25% of the families selected using independent culling at each environment, the number of families was generally higher using independent culling than using either b or PC alone (Table 4). Young (1961) concluded that selection index was always more efficient than either independent culling or tandem selection and that this superiority was maximum when the traits had similar economic weights. Therefore, selection indices (SIBYLD and SIPCYLD) that involved the stability parameters and mean yield in their derivation were compared as indirect selection criteria versus direct selection for yield using the same selection pressure of 10%.

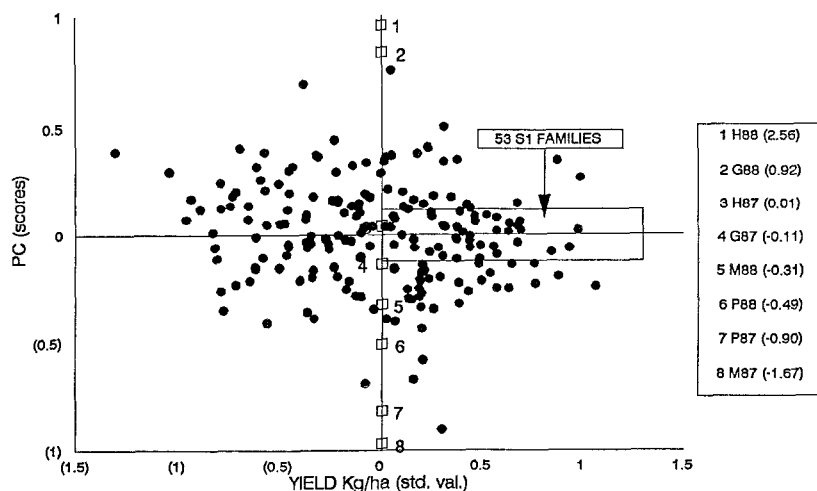


Fig. 3. Biplot from the additive main effects and multiplicative interaction (AMMI) model and S_1 families selected on the basis of principal component (PC) scores close to 0 and mean yield above the average in TP24D sorghum population

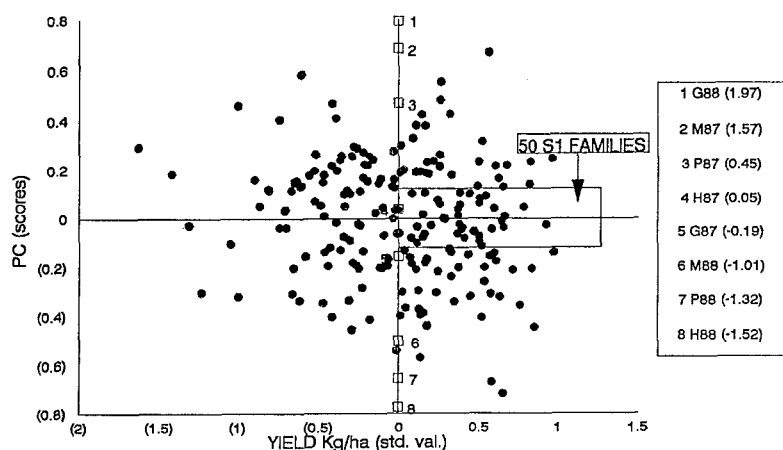


Fig. 4. Biplot from the additive main effects and multiplicative interaction (AMMI) model and S_1 families selected on the basis of principal component (PC) scores close to 0 and mean yield above the average in KP9B sorghum population

The SIBYLD index included b and the overall mean yield, whereas SIPCYLD used PC and the overall mean yield. Both indices were relatively more efficient than indirect selection for b or PC alone (Table 3). The ranges for SIBYLD were from 74% to 255% for TP24D and 53% to 213% for KP9B. The ranges for SIPCYLD were from 66% to 215% for TP24D and 52% to 220% for KP9B. The lowest relative efficiency for predicted gain from indirect selection for SIBYLD and SIPCYLD in both populations was in the poorest environment.

The better performance of the indices, in relation to selection for either b or PC alone, was due to the ability of the index to incorporate appropriate weights to both the stability parameter and yield. Eskridge and Johnson (1991) showed the advantage in the selection of genotypes with broader adaptation from using indices that included the mean yield and a stability parameter. The superiority of the index over independent culling, based on the number of families in common (Table 4), could have been due to the differences in selection intensity or to the differ-

ences between independent culling and selection index in relation to the weights given to b -values and yield.

An alternative approach to indirect selection used selection indices that involved fewer environments in their estimation than the stability parameter (Zavala-Garcia et al. 1992). The relative efficiencies of these indices are shown in Table 3. The higher relative efficiencies of mean productivity (MBIW), rank summation (RBIW), and selection index (SIY) clearly illustrate their superiority over b or PC alone. However, their efficiencies relative to those of SIBYLD or SIPCYLD were similar for TP24D and equal or lower for KP9B, except in the poorest environment, where SIY was the best (94%). The number of families in common in the top 10% with direct selection were very similar between SIBYLD, SIPCYLD, MBIW, RBIW, and SIY and more than the number with b and PC alone. Both SIBYLD and SIPCYLD were superior for TP24D, especially in relation to the use of the overall mean (17 families in common out of 20). For KP9B, the superiority of the selection indices was higher

Table 3. Relative efficiencies of predicted gain from indirect selection in relation to predicted gain from direct selection for grain yield using the coefficient of regression (b); principal component (PC) score; selection index using b and mean yield (SIBYLD); selection index using PC and mean yield (SIPCYLD); mean productivity between the best, an intermediate, and the worst environments (MBIW); a selection index using grain yield from environments selected from clustering the matrix from genetic correlations and heritabilities (SIY); and rank summation between the best, an intermediate, and the worst environments (RBIW) at eight environments (Mead, Neb.; Hesston, Garden City, and Parsons, Kan., during 1987 and 1988) and the overall for TP24D and KP9B sorghum populations

Environment	Mean kg ha ⁻¹	b %	PC %	SIBYLD %	SIPCYLD %	MBIW %	SIY %	RBIW %
<i>TP24D</i>								
Mead 1987	4580	61	47	93	93	95	92	96
Mead 1988	4220	54	18	104	101	84	92	82
Hesston 1987	2676	44	41	92	95	76	86	80
Hesston 1988	4154	43	-23	74	66	51	73	52
Garden City 1987	3035	89	47	149	146	127	149	128
Garden City 1988	1221	17	-36	83	78	79	73	85
Parsons 1987	4103	57	31	150	150	148	146	151
Parsons 1988	2909	2	56	99	106	80	62	80
Overall	3376	112	51	255	251	198	211	202
<i>KP9B</i>								
Mead 1987	4558	4	-21	91	88	101	106	103
Mead 1988	4067	33	40	115	116	81	96	80
Hesston 1987	2734	-9	13	80	87	68	64	67
Hesston 1988	3242	12	49	97	106	57	72	57
Garden City 1987	3024	13	43	105	112	88	82	88
Garden City 1988	1754	-27	-53	53	52	88	94	90
Parsons 1987	4554	48	39	122	120	74	102	72
Parsons 1988	3797	31	61	107	114	71	73	69
Overall	3470	23	41	213	220	162	177	162

Table 4. Number of families in common between the top 10% yielding families from eight environments (Mead, Neb.; Hesston, Garden City, and Parsons, Kan., during 1987 and 1988) and overall mean with: (1) the top 10% families using the coefficient of regression (b); principal component (PC) score; selection index involving b and mean yield (SIBYLD); selection index involving PC and mean yield (SIPCYLD); mean productivity between the best, an intermediate, and the worst environments (MBIW), selection index using yield from environments selected from clustering the matrix of genetic correlations and heritabilities (SI1); and rank summation between the best, an intermediate, and the worst environments (RBIW), and (2) the top 25% of the families using independent culling selection for TP24D and KP9B sorghum populations

Environment	Mean kg ha ⁻¹	Top 10%							Independent culling (25%)	
		b	PC	SIBYLD	SIAMYLD	MBIW	SI1	RBIW	Mean yield and b	Mean yield and PC
<i>TP24D</i>										
Mead 1987	4580	3	4	12	10	1	12	9	7	10
Mead 1988	4220	1	4	8	5	6	5	5	7	8
Hesston 1987	2676	4	4	6	7	5	6	5	6	12
Hesston 1988	4154	1	2	5	6	4	9	4	6	9
Garden City 1987	3035	3	2	7	7	7	6	9	5	8
Garden City 1988	1221	3	5	5	4	7	4	7	7	11
Parsons 1987	4103	6	3	7	8	6	6	7	6	7
Parsons 1988	2902	3	1	3	4	2	4	3	9	6
Overall mean	3362	3	5	17	17	13	13	15	10	14
<i>KP9B</i>										
Mead 1987	4558	2	3	8	9	9	12	12	3	9
Mead 1988	4067	0	5	11	10	3	9	5	3	12
Hesston 1987	2734	1	5	6	6	5	6	5	3	9
Hesston 1988	3242	3	2	8	9	2	5	2	8	7
Garden City 1987	3024	4	1	7	7	8	4	7	7	7
Garden City 1988	1754	3	2	3	3	1	10	9	6	4
Parsons 1987	4554	2	6	7	5	3	5	3	2	10
Parsons 1988	3797	4	4	8	9	2	2	2	8	8
Overall mean	3470	4	5	15	16	9	12	7	9	9

in each environment and with the overall mean, except for the poorest environment (Garden City 1988), where MBIW, RBIW, and SIY had nearly 3 times as many families in common with direct selection in this environment.

Neither the coefficient of regression (b) nor the principal component score (PC) alone had high relative efficiency as an indirect selection criterion to improve mean yield in the various environments because of their low heritability in relation to yield per se in some environments and low genetic correlations in others. However, when they were combined with the overall mean to create an index (SIBYLD and SIPCYLD), the relative efficiency of indirect selection increased dramatically in both populations. Selection using independent culling resulted in both a higher selection intensity and fewer families in common with direct selection compared with SIBYLD and SIPCYLD. Mean productivity (MBIW), rank summation (RBIW), and selection index (SIY) were less efficient with fewer environments except the poorest environment for KP9B, where SIY was superior. In terms of the efficient use of resources in a breeding program, MBIW, RBIW, and SIY required fewer environments to estimate and resulted in little loss in predicted gain from indirect selection at each environment separately. They would be superior unless information from the range of environments was available, in which case the selection indices, SIBYLD and SIPCYLD, would be more efficient to use in a given target area.

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