

## Correlation among Yield Stability Parameters in Common Bean

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### ABSTRACT

Phenotypic yield stability is a trait of special interest for plant breeders. Many statistical procedures are available for stability analysis, each of them allowing for different interpretations. The objective of the present study was to determine the degree of correlation among the 13 statistical parameters that can be used for the analysis of phenotypic stability. Such correlations could be used to assess the extent to which these 13 parameters identify unique genetic effects. Yield data were obtained from 12 yield trials involving 76 common bean (*Phaseolus vulgaris* L.) genotypes and 12 location-year production environments in Brazil. The stability statistics were divided in four groups according to the structure from which they were derived. On the basis of rank correlation, it was concluded that (i) there were highly significant correlations between many of the stability statistics (among and within groups) indicating that several of the statistics probably measure similar aspects of phenotypic stability; (ii) mean yields were positively correlated with many of the stability statistics; (iii) there was an association between the Group A statistics (variances and ranges) and the Group C statistics (regression and determination coefficients), and a similar association between the Group B (ecovariance) and Group D (variance of deviations from regression) statistics; (iv) the segmented linear regression coefficient ( $b_{Li}$ ) was overall the most independent parameter, indicating that the other stability statistics do not satisfactorily reflect genotypic responses in poor environments; (v) the strong correlation between the regression coefficients and the coefficients of determination indicates that the latter are not needed to measure the predictability of the estimated genotypic response; and (vi) the variance of the deviations from regression can provide assessment of the relative contribution of the genotype to the genotype  $\times$  environment interaction as well as its biological stability.

A VARIETY of methods and statistics are currently available for the evaluation of phenotypic stability of plant cultivars. However, the stability estimate provided by a given procedure may be interpretatively different from stability that the breeder is actually seeking. Opting for the use of a particular method or parameter has been difficult even for those who are authorities in the study of genotype by environment ( $G \times E$ ) interaction. The evolution of methodology has resulted in a conceptual complexity that Becker and Léon (1988) have described as "the word adaptation today has great adaptability," so many are the different meanings that are attributed to phenotypic stability, yield stability, and adaptation.

The historic evolution of  $G \times E$  methodology illustrates the point. The earliest form is possibly the procedure proposed by Roemer (1917) who used phenotypic variance across environments ( $s^2$ ) as a parameter, which was later employed by Casler and Hovin (1984). Similar methods have been suggested by Francis and Kannenberg (1978) and Langer et al. (1979), who respectively used the phenotypic coefficient of variation ( $CV_i$ ) and the range in cultivar yields ( $RI_i$  and  $R2_i$  indices). Other

methods have been based on the partitioning of  $G \times E$  interaction into variance components that are attributed to each cultivar (Plaisted and Peterson, 1959; Plaisted, 1960; Wricke, 1965). Wricke (1965) called his parameter ecovariance ( $E_i$ ). A different approach was followed by St-Pierre et al. (1967) who evaluated cultivar adaptation as a percentage of genotype adaptability, which was defined as the proportion of environments in which a given cultivar outperformed the average of all genotypes included in the trial.

More widely used methods, however, are those based on regression. Finlay and Wilkinson (1963) adapted the linear regression technique of Yates and Cochran (1938) to measure the adaptation of barley cultivars. A linear regression coefficient (which was used as stability parameter) was determined for each genotype by regressing individual genotype yield performance against the environmental means. Eberhart and Russell (1966) proposed the use of variance of deviations from regression ( $s^2d_i$ ) to measure cultivar stability, and regression coefficient ( $b_i$ ) to evaluate cultivar adaptation. Pinthus (1973) and Bilbro and Ray (1976) favored the coefficient of determination ( $r_i^2$ ) over variance of deviations from regression as a measure of the predictability of the estimated response (stability). A number of other regression methods have been proposed (Bucio Alanis, 1966; Perkins and Jinks, 1968; Knight, 1970; Tai, 1971; Verma et al., 1978).

Silva and Barreto (1985) proposed the bi-segmented linear regression procedure of Verma et al. (1978). This method is based on two linear regression coefficients ( $b_{1i}$  and  $b_{2i}$ ) for the separate evaluation of the responses of a cultivar to poor and favorable environments respectively. Additional modifications were later introduced by Cruz et al. (1989).

The different stability concepts that prompted the development of these various methods were categorized by Becker (1981) to two interpretations: biological stability (constant performance) and agronomical stability (predictable performance). Later, Becker and Léon (1988) renamed these static stability and dynamic stability respectively. Lin et al. (1986) suggested three stability interpretations: Type 1 (biological stability, i.e.,  $s_i^2 \rightarrow 0$ ), Type 2 (phenotypic response of the genotype to environments parallels the mean response of all tested genotypes, i.e.,  $b_i \rightarrow 1$ ) and Type 3 (high confiability of estimated response, i.e.,  $s^2d_i \rightarrow 0$ ). The authors also identified four groups of statistical parameters needed for the evaluation of these types of stability: Group A (estimated from the genotypic effects), Group B (estimated from the genotype by environment interaction variance), Group C (estimated by the regression coefficients), and Group D (estimated from the deviations from regression). The same authors also pointed out that the use of parameters belonging to different concepts may lead to different rankings of genotypes in terms of their stability.

Paroda (1976), Santos et al. (1982), Langer et al. (1979), Becker (1981), and Becker and Léon (1988)

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have commented on the similarities among these stability parameters as well as on the consequences of the utilization of different parameters for an ordering of genotypes. These authors showed that several of the parameters either measure the same stability aspect, or measure the effects of very similar gene groups.

The present work was undertaken in order to increase the amount of information related to this subject by quantifying any associations that might exist among stability statistics derivable from seven different methods (Roemer, 1917; Finlay and Wilkinson, 1963; Wricke, 1965; Eberhart and Russell, 1966; St-Pierre et al., 1967; Langer et al., 1979; Silva and Barreto, 1985). These statistics belong to all four groups identified by Lin et al. (1986). The correlations we present should help plant breeders choose the most independent and informative statistics to use in evaluation of genotypes.

## MATERIALS AND METHODS

Experimental data were obtained from bean yield trials coordinated by the Brazilian Enterprise for Agricultural Research (EMBRAPA) through the National Research Center for Rice and Bean (CNPAP). The trials were conducted at eight locations in Brazil during the agricultural years 1984-1985 and 1985-1986, and provided a total of 12 environments (Table 1). Sowing dates and density, fertilizer applications, and other cultural practices followed the recommendations of the National Bean Research Program (Duarte and Zimmerman, 1992). Plot size was 8 m<sup>2</sup> (four rows, 4 m long, 0.5 m between adjacent rows).

Trials consisted of 100 treatments (lines and cultivars) evaluated in a square (10 × 10) lattice design with two replications in each environment. Of the 100 genotypes, only 76 were grown at all locations and years. All the genotypes belonged to the Mulatinho commercial group (Vieira, 1967) with the cultivar Carioca used as a stability check. Carioca has a cream colored seed coat, with brown stripes. No early maturity genotype was used in the study. Harvest occurred between 84 and 90 d after sowing in all environments.

Genotypic yield data were subjected to an analysis of variance. Because the combinations of years and locations were not balanced, the trials listed in Table 1 were treated as 12 production environments. Stability statistics were calculated for each of the seven methods reported in the literature [Roemer (1917), Finlay and Wilkinson (1963), Wricke (1965), Eberhart

and Russell (1966), St-Pierre et al. (1967), Langer et al. (1979), and Silva and Barreto (1985)].

Parameter definitions are presented in the following section, with  $Y_{ij}$  representing the yield of the  $i$ th genotype in the  $j$ th environment,  $n$  is the number of genotypes, and  $m$  the number of environments. The grand mean yield of each genotype was estimated by

$$Y_i = Y_i/m$$

### Method of Roemer (1917)

Phenotypic variance ( $s_i^2$ ) was estimated for each genotype as:

$$s_i^2 = \left[ \sum_j Y_{ij}^2 - (Y_i)^2/m \right] / (m - 1)$$

### Method of Finlay and Wilkinson (1963)

Yield data were log transformed so that  $Y'_{ij} = \log Y_{ij}$ . The regression coefficient was calculated as:

$$b'_i = \left[ \sum_j Y'_{ij} \bar{X}'_j - (Y'_i \sum_j \bar{X}'_j)/m \right] / \left[ \sum_j \bar{X}'_j{}^2 - (\sum_j \bar{X}'_j)^2/m \right]$$

with:

$$\bar{X}'_j = Y'_j/n$$

### Method of Wricke (1965)

Ecovalence ( $E_i$ ), was estimated for each genotype as:

$$E_i = \sum_j d_{ij}^2$$

with

$$d_{ij} = Y_{ij} - \bar{Y}_i - \bar{Y}_j + \bar{Y}_{..}$$

### Method of Eberhart and Russell (1966)

Parameters  $b_i$  and  $s^2 d_i$  were estimated for each genotype by linear regression of  $Y_{ij}$  over the environmental index  $I_j$  as follows:

$$I_j = \bar{Y}_j - \bar{Y}_{..}$$

$$b_i = \sum_j Y_{ij} I_j / \sum_j I_j^2$$

and

$$s^2 d_i = \left\{ \left( \sum_j Y_{ij}^2 - Y_i^2/m \right) - \left[ \left( \sum_j Y_{ij} I_j \right)^2 / \sum_j I_j^2 \right] \right\} / (m - 2)$$

In the expression of  $s^2 d_i$ , we did not subtract  $s^2 e/r$  (pooled error), since this component is constant for all genotypes and it does not alter rank orders.

The coefficient of determination ( $r_i^2$ ), a statistic suggested by Pinthus (1973) was determined as follows:

$$r_i^2 = b_i^2 s_{I_j}^2 / s_i^2$$

with:

$$s_{I_j}^2 = \sum_j I_j^2 / (m - 1)$$

Table 1. Test locations and years in Brazil and the respective mean yields.

Location/state	Year	Mean yield
		kg/ha
Goiânia/Goiás†	1984-1985	517
Goiânia/Goiás†	1984-1985	1186
Goiânia/Goiás	1985-1986	796
Vilhena/Rondonia	1985-1986	921
Bio Branco/Acre	1984-1985	942
Rio Branco/Acre	1985-1986	678
Lavras/Minas Gerais	1984-1985	877
Irecê/Bahia	1984-1985	550
Irecê/Bahia	1985-1986	813
Nova Soure/Bahia	1984-1985	1079
Ipirá/Bahia	1984-1985	768
Aracaju/Sergipe	1984-1985	859
Average	—	832

† Two environments from the same location and year but under two different soil fertility levels.

### Method of St-Pierre et al. (1967)

Percent adaptability of a genotype ( $Ad_i$ ) was estimated as  $Ad_i = (N_i \cdot 100)/m$ , where  $N_i$  is the number of environments in which the mean of the  $i$ th genotype ( $Y_{ij}$ ) was superior to the environmental mean ( $Y_j$ ).

### Method of Langer et al. (1979)

The  $RI_i$  and  $R2_i$  parameters were estimated as follows:

$$RI_i = Y_{ih} - Y_{il}$$

and

$$R2_i = Y_{ib} - Y_{iw}$$

where  $Y_{ih}$  is the highest and  $Y_{il}$  is the lowest mean yield of the  $i$ th genotype among the 12 environments, and  $Y_{ib}$  and  $Y_{iw}$  are the mean yields of the  $i$ th genotype in the environments with the best (highest) and the worst (lowest) yields, respectively.

### Method of Silva and Barreto (1985)

The linear regression coefficients  $b1_i$  and  $b2_i$ , which are the responses of the  $i$ th genotype in those environments that have a negative  $I_j$  (i.e.  $\bar{Y}_j - \bar{Y} < 0$ ) or a positive  $I_j$ , respectively, were estimated as follows:

$$b1_i = \left[ m \sum_j X2_j^2 \left( \sum_j X1_j Y_{ij} - \sum_j X2_j Y_{ij} \right) + \sum_j X2_j \left( \sum_j X2_j^2 Y_i - \sum_j X2_j \sum_j X1_j Y_{ij} \right) \right] / d$$

$$b2_i = b1_i + \left( m \sum_j X1_j^2 \sum_j X2_j Y_{ij} - \sum_j X1_j^2 \sum_j X2_j Y_i - m \sum_j X2_j^2 \sum_j X1_j Y_{ij} \right) / d$$

with:

$$d = m \sum_j X2_j^2 \left( \sum_j X1_j^2 - \sum_j X2_j^2 \right) - \sum_j X1_j^2 \left( \sum_j X2_j \right)^2$$

where  $X1_j$  is the environmental index as proposed by Eberhart and Russell (1966), and  $X2_j = X1_j$  if  $X1_j \geq 0$  and  $X2_j = 0$  if  $X1_j \leq 0$ .

The coefficient of determination for the segmented regression of each genotype ( $R_i^2$ ) was estimated as:

$$R_i^2 = \left[ b0_i Y_i + b1_i \sum_j X1_j Y_{ij} + (b2_i - b1_i) \sum_j X2_j Y_{ij} - (Y_i)^2 / m \right] / \left[ \sum_j Y_{ij}^2 - (Y_i)^2 / m \right]$$

$$b0_i = \left[ \sum_j X2_j^2 Y_i \left( \sum_j X1_j^2 - \sum_j X2_j^2 \right) + \sum_j X2_j \left( \sum_j X2_j^2 \sum_j X1_j Y_{ij} - \sum_j X1_j^2 \sum_j X2_j Y_{ij} \right) \right] / d$$

### Estimation of Parameter Correlation

The correlation among the various adaptation and phenotypic stability parameters was measured by Spearman's rank correlation. The correlation coefficient ( $r_{spp'}$ ) was estimated for each pair of parameters  $p$  and  $p'$  as follows:

$$r_{spp'} = 1 - (6 \sum_i d_i^2) / (n^3 - n)$$

where  $d_i$  is the difference between the ranks of the  $i$ th genotype for parameters  $p$  and  $p'$ .

The hypothesis  $H_0: r_{spp'} = 0$  was tested by the Student  $t$ -test

$$t = r_{spp'} \sqrt{(n-2)/(1-r_{spp'}^2)}$$

with  $(n-2)$  degrees of freedom.

For interpretation of the correlations, the stability statistics were placed into four groups based on the classification of Lin et al. (1986). Group A:  $s_i^2$ ,  $Ad_i$ ,  $RI_i$  and  $R2_i$ ; Group B:  $E_i$ ; Group C:  $b_i$ ,  $b1_i$ ,  $b2_i$ ,  $r_i^2$ , and  $R_i^2$ ; Group D:  $s^2 d_i$ .

## RESULTS AND DISCUSSION

Reports can be found in the scientific literature that deals with the conceptual interpretation of a diversity of published stability statistics (Langer et al., 1979; Becker, 1981; Lin et al., 1986; Becker and Léon, 1988). In general, these reports involved only a subset of the existing statistics and did not include all groups that are characteristic of stability parameters. In the common bean, a stability analysis of a set of genotypes is typically limited to the derivation of stability parameters by one of the published methods. Determining the extent of the association among stability statistics in this species, would help bean breeders in choosing stability parameters for discriminating among genotypes in a manner that best fits their concept of stability.

The analysis of variance of yields of the 76 genotypes in the 12 production environments revealed a large environmental effect (Table 2), which reflected the two-fold range in the mean yields of 12 environments (Table 1). The significance of the  $G \times E$  interaction and its linear and non linear components (Table 2) demonstrated that genotypes differed in their responses to this environmental variation. This result, and the large number of genotypes, indicated that this data base would be suitable for estimating the various stability statistics (Table 3), and for calculating the correlations among them (Table 4).

The values of the Spearman correlation coefficient are

Table 2. Analysis of variance of the seed yield (kg/ha) of 76 common bean genotypes tested in the twelve Brazilian environments listed in Table 1.

Sources of variations	DF	MS
Blocks/Environment	12	593 739.78**
Environments (E)	11	2 882 192.64**
Genotypes (G)	75	108 606.46**
$G \times E$	825	53 345.04**
E within G (E + $G \times E$ )	836	90 566.72**
E (linear)	1	31 699 900.00**
$G \times E$ (linear)	75	78 402.20**
Pooled deviations	760	50 175.90**
Pooled Error	900	23 024.29

\*\* Significant at the 1% probability level.

Table 3. Genotypic mean yields ( $\bar{Y}_i$ ) for 76 common bean genotypes and their stability parameters calculated by the methods proposed by Roemer, 1917 ( $s_i^2$ ), Finlay and Wilkinson, 1963 ( $b_i$ ); Wriake, 1965 ( $E_i$ ); Eberhart and Russell, 1966 ( $b_i$ ,  $s^2d_i$ ,  $r_i^2$ ); St-Pierre et al., 1967 ( $Ad_i$ ); Langer et al., 1979 ( $RI_i$ ,  $R2_i$ ); and Silva and Barreto, 1985 ( $b1_i$ ,  $b2_i$ ,  $R_i^2$ ).

Genotype	$\bar{Y}_i$	$s_i^2$	$b_i$	$E_i$	$b_i$	$s^2d_i$	$r_i^2$	$Ad_i$	$RI_i$	$R2_i$	$b1_i$	$b2_i$	$R_i^2$
L 12155	886.4	57 072.4	0.90	228 962	0.98	22 880.7	0.64	58.3	725.7	393.3	1.17	-0.38	0.64
Aroana	784.8	70 482.6	0.32	942 023	0.30	73 773.6**	0.05	41.7	884.5	425.0	0.23	0.14	0.05
L 12118	816.8	78 386.3	1.34	360 380	1.10	35 613.8	0.59	33.3	883.2	531.7	1.93	-1.67	0.72
L 11152	915.1	83 312.4	0.85	497 277	1.00	49 731.9*	0.46	58.3	861.7	803.3	0.92	0.17	0.46
LM 21303-0	1013.5	132 404.0	1.35	622 582	1.50	51 863.5*	0.64	75.0	1088.4	895.0	2.04	-1.09	0.68
82 PVBZ 1901	726.6	180 000.0	0.89	1 513 610	1.06	151 220.0**	0.24	50.0	1398.2	668.3	-0.32	2.76	0.39
82 PVBZ 1718	957.1	148 200.0	1.32	655 867	1.67	46 991.8*	0.71	66.7	1254.9	938.3	0.92	1.50	0.77
82 PVBZ 1777	812.9	134 838.0	0.96	837 847	1.27	80 670.3**	0.46	58.3	1277.8	745.0	0.04	2.48	0.63
L 11130	903.1	79 862.9	1.04	417 820	1.05	41 674.0	0.53	66.7	845.0	845.0	1.47	-0.85	0.56
LM 21525-0	821.6	49 721.8	0.59	458 160	0.61	39 356.7	0.28	33.3	758.0	18.3	0.95	-0.69	0.32
LM 10034-0	809.0	45 939.2	0.72	405 544	0.62	34 521.7	0.32	41.7	668.3	396.7	0.74	-0.25	0.32
Mulatinho V. Roxa	885.8	87 311.2	1.14	399 161	1.17	38 675.6	0.60	66.7	893.3	835.0	0.86	0.62	0.61
L 10238	777.5	76 811.0	1.29	559 686	0.84	54 928.7**	0.35	33.3	847.2	606.7	2.08	-2.48	0.65
L 11090	779.9	33 587.5	0.18	637 203	0.18	53 609.5	0.04	50.0	626.6	275.0	0.25	-0.15	0.04
A331	706.7	126 507.0	1.72	641 885	1.40	57 566.2**	0.59	33.3	1184.1	921.7	0.92	0.95	0.61
ESAL 501	888.7	61 590.5	0.89	249 238	1.01	24 921.7	0.63	58.3	934.6	560.0	0.85	0.33	0.64
LM 21525-0	846.1	148 696.0	1.66	640 570	1.69	44 046.7*	0.73	50.0	1168.9	1060.0	1.74	-0.09	0.73
LM 10402-0	888.1	116 168.0	1.06	496 835	1.44	41 757.0	0.67	41.7	1222.8	1075.0	0.45	1.97	0.80
82 PVBZ 1783	956.4	75 804.1	0.58	691 863	0.67	64 652.2**	0.22	66.7	932.0	241.7	0.31	0.72	0.25
L 11132	765.8	46 015.8	0.56	438 282	0.58	36 520.7	0.28	25.0	688.3	688.3	0.66	-0.16	0.28
L 10099	891.0	79 263.0	1.22	177 116	1.33	13 098.8	0.85	50.0	900.0	900.0	1.42	-0.18	0.85
LM 21306-0	923.1	95 056.6	1.20	301 613	1.39	23 765.1	0.77	66.7	1195.0	1195.0	1.08	0.63	0.79
A300	835.1	127 179.0	1.51	633 125	1.42	56 031.9**	0.60	58.3	1167.2	968.3	1.28	0.28	0.60
LM30877-0	789.6	35 260.5	0.88	138 949	0.80	12 202.2	0.69	41.7	688.1	520.0	1.00	-0.41	0.70
A 275	629.3	62 848.0	1.07	636 975	0.57	55 811.4**	0.19	16.7	890.7	241.7	1.49	-1.85	0.39
LM 21322-0	978.4	160 411.0	0.88	966 544	1.46	87 972.3**	0.50	66.7	1501.6	1260.0	0.39	2.13	0.61
A329	732.0	26 981.6	0.58	303 752	0.49	19 598.4	0.34	16.7	531.7	425.0	0.75	-0.51	0.38
EMGOPA 201	928.9	77 299.2	1.01	299 711	1.16	28 909.2	0.66	75.0	957.8	586.7	1.31	-0.31	0.66
A 317	890.1	96 303.3	1.01	809 862	0.80	79 305.3**	0.25	50.0	1285.1	-18.3	0.80	-0.01	0.25
L 11080	773.4	57 837.5	0.88	364 254	0.83	35 165.5	0.45	33.3	898.3	898.3	0.82	0.01	0.45
L 11077	815.4	66 366.9	1.20	239 682	1.09	23 651.8	0.68	33.3	810.0	810.0	1.49	-0.80	0.71
82 PVBZ 1758	777.2	75 539.1	1.45	193 134	1.26	16 402.1	0.80	33.3	1042.0	801.7	1.37	-0.22	0.80
L 10146	792.8	48 373.2	0.84	376 266	0.69	33 538.0	0.37	41.7	724.2	370.0	1.21	-1.05	0.45
LM 10033-0	758.0	45 030.4	0.71	368 177	0.65	31 780.8	0.36	41.7	685.0	460.0	0.85	-0.40	0.37
L 11093	858.1	83 862.3	0.91	523 318	0.98	52 316.7*	0.43	41.7	1026.7	1026.7	1.08	-0.20	0.43
Parana 1	822.3	66 849.0	0.62	657 518	0.59	58 854.0**	0.20	50.0	840.0	345.0	1.16	-1.13	0.27
Cornell 49242	895.0	107 033.0	1.21	366 074	1.47	27 305.2	0.77	58.3	1266.3	1055.0	0.71	1.52	0.85
82 PVBZ 1529	884.2	88 724.5	0.67	654 958	0.88	64 947.2**	0.33	66.7	1060.7	178.3	0.80	0.17	0.34
A 156	710.9	77 935.6	1.55	289 524	1.18	27 597.4	0.68	25.0	976.6	601.7	1.49	-0.62	0.70
L 10111	912.2	26 812.1	0.50	223 768	0.59	15 205.6	0.48	75.0	635.2	298.3	0.73	-0.29	0.50
82 PVMX 1638	926.2	227 798.0	1.98	1 015 010	2.29	32 437.6	0.87	58.3	1586.6	1586.6	1.38	1.81	0.92
82 PVBZ 1767	613.4	41 654.2	1.08	279 241	0.71	24 526.2	0.46	8.3	704.8	243.3	0.44	0.55	0.49
LM 21387-0	838.1	81 364.8	1.23	466 700	1.01	46 667.2*	0.48	58.3	922.4	451.7	2.07	-2.11	0.68
LM 30864-0	783.5	77 173.3	0.59	764 421	0.60	69 812.1**	0.18	33.3	874.9	423.3	0.69	-0.17	0.18
L 11150	882.3	50 812.5	0.69	493 742	0.58	41 953.2	0.25	50.0	758.3	546.7	1.50	-1.85	0.50
ESAL 508	881.8	51 152.4	0.74	294 488	0.82	28 122.6	0.50	58.3	747.8	380.0	0.92	-0.20	0.50
A 274	751.8	81 098.5	0.89	746 968	0.67	70 264.9**	0.21	41.7	1030.0	441.7	1.58	-1.82	0.36
L 11088	706.4	71 059.7	0.89	750 361	0.54	66 115.6**	0.15	33.3	890.0	730.0	1.16	-1.24	0.24
82 PVBZ 1879	771.3	162 050.0	1.89	926 668	1.53	81 137.7**	0.54	16.7	1300.8	1260.0	1.83	-0.61	0.55
82 PVMX 1637	897.1	145 575.0	1.73	580 106	1.72	36 152.3	0.77	50.0	1571.6	1571.6	1.07	1.31	0.82
L 11133	833.8	49 333.5	1.12	369 272	0.71	33 369.8	0.39	58.3	820.0	820.0	1.20	-0.98	0.46
82 PVBZ 1843	704.2	82 928.8	0.93	845 801	0.58	77 209.9**	0.15	25.0	1085.0	300.0	1.60	-2.05	0.34
L 11076	840.8	33 861.5	0.59	364 746	0.51	26 431.2	0.29	58.3	602.8	466.7	0.99	-0.96	0.39
A 154	861.4	97 384.4	1.03	470 221	1.22	45 001.5*	0.58	58.3	1021.0	490.0	0.79	0.86	0.61
A 266	833.7	66 536.6	0.81	319 421	0.99	31 945.3	0.56	50.0	958.3	958.3	0.31	1.37	0.67
ESAL 506	1045.3	81 717.2	0.93	245 290	1.28	21 185.8	0.76	100.0	904.2	821.7	1.12	0.33	0.77
BAT 841	770.6	100 985.0	1.22	518 172	1.21	49 975.6*	0.55	41.7	1006.0	730.0	0.86	0.70	0.57
L 10110	897.6	101 749.0	1.53	389 254	1.37	33 067.0	0.70	50.0	1106.0	788.3	1.86	-0.98	0.74
LM 10367-0	826.8	66 107.6	1.04	335 396	0.97	33 504.4	0.54	41.7	1044.3	555.0	1.23	-0.52	0.55
A 344	918.9	92 388.4	1.04	296 923	1.36	24 225.1	0.76	58.3	1142.9	883.3	0.76	1.20	0.82
Carioca	817.5	52 454.6	0.88	302 002	0.83	28 993.7	0.50	41.7	852.2	378.3	1.11	-0.55	0.52
L 13497	815.6	83 827.1	1.31	433 304	1.09	43 027.6*	0.53	41.7	962.0	800.0	1.61	-1.06	0.58
ESAL 505	988.4	172 524.0	0.79	1 135 250	1.41	106 384.0**	0.44	75.0	1555.2	1361.7	-0.20	3.23	0.67
LM 30068-0	742.1	27 265.2	0.59	231 346	0.58	15 854.9	0.47	16.7	581.7	581.7	0.63	-0.10	0.47
L 11086	788.4	67 267.6	0.56	702 751	0.54	61 625.5**	0.17	41.7	856.6	331.7	0.87	-0.65	0.19
CP 1035	603.3	92 902.6	1.40	850 209	0.71	81 413.2**	0.20	16.7	938.3	158.3	1.82	-2.22	0.40
A 254	900.0	131 028.0	0.95	967 169	1.07	96 526.6**	0.33	50.0	1111.7	435.0	1.57	-1.01	0.36
ESAL 509	821.7	85 256.3	0.96	519 320	1.00	51 936.8*	0.45	41.7	1048.8	433.3	1.05	-0.10	0.45
A 251	1034.3	170 540.0	1.12	950 126	1.61	79 518.8**	0.58	66.7	1466.8	1206.6	0.75	1.72	0.64
82 PVBZ 1723	667.3	83 793.6	1.05	833 870	0.61	76 891.1**	0.17	41.7	882.7	303.3	0.39	0.44	0.17
ESAL 504	1061.7	471 192.0	1.56	3 487 460	2.53	250 800.0**	0.52	50.0	1899.4	1743.3	0.94	3.18	0.60
LM 30995-0	749.8	31 927.6	0.32	528 879	0.29	31 684.9	0.10	50.0	566.7	86.7	0.71	-0.85	0.18
LM 10027-1	730.3	72 994.6	0.94	451 186	0.92	44 866.3*	0.44	8.3	964.1	673.3	0.74	0.37	0.45
A323	775.9	122 091.0	1.09	909 205	1.02	90 909.8**	0.32	41.7	1155.3	478.3	0.14	1.76	0.42
IPA 74-19	779.0	64 463.1	0.44	728 274	0.48	61 419.8**	0.13	41.7	781.2	688.3	0.21	0.53	0.15
L 10323	852.4	53 131.9	0.82	288 497	0.85	27 973.2	0.52	41.7	855.0	855.0	0.82	0.06	0.52

\*, \*\*  $s^2d_i$  values different from error variance at the 5 and 1% probability levels, respectively.

† LSD for yield is 259.3 Kg/ha (Tukey test for 5% probability level).

Table 4. Rank correlation coefficients among the various yield stability statistics, grouped by stability concept, and estimated by the methods proposed by Roemer, 1917 ( $s_i^2$ ); St-Pierre et al., 1967 ( $Ad_i$ ); Langer et al., 1979 ( $RI_i$ ,  $R2_i$ ); Wricke, 1965 ( $E_i$ ); Finlay and Wilkinson, 1963 ( $b_i$ ); Eberhart and Russell, 1966 ( $b_i$ ,  $s^2d_i$ ,  $r_i^2$ ); and Silva and Barreto, 1985 ( $b1_i$ ,  $b2_i$ ,  $R_i^2$ ).

Parameters	Group A†				Group B†		Group C†				Group D†	
	$s_i^2$	$Ad_i$	$RI_i$	$R2_i$	$E_i$	$b'_i$	$b_i$	$b1_i$	$b2_i$	$r_i^2$	$R_i^2$	$s^2d_i$
$Y_i$	0.38**	0.83**	0.37**	0.43**	-0.04	0.13	0.55**	0.05	0.49**	0.50**	0.49**	-0.08
$s_i^2$		0.32**	0.92**	0.57**	0.59**	0.64**	0.80**	0.10	0.69**	0.36**	0.41**	0.58**
$Ad_i$			0.27*	0.26*	0.03	0.00	0.39**	-0.10	0.42**	0.32**	0.32**	-0.03
$RI_i$				0.57**	0.50**	0.61**	0.78**	0.06	0.72**	0.39**	0.44**	0.49**
$R2_i$					0.04	0.52**	0.77**	0.07	0.69**	0.65**	0.67**	-0.01
$E_i$						0.05	0.07	-0.14	0.12	-0.48**	-0.38**	0.93**
$b'_i$							0.76**	0.55**	0.42**	0.64**	0.67**	0.06
$b_i$								0.21	0.82**	0.81**	0.81**	0.05
$b1_i$									-0.34**	0.29*	0.33**	-0.10
$b2_i$										0.62**	0.57**	0.08
$r_i^2$											0.94**	-0.50**
$R_i^2$												-0.41**

\*, \*\* Significant at the 5 and 1% probability level, respectively.

† Group A statistics are based on the average genotypic effect (variances, ranges); Group B statistic based on the GE sum of squares (ecovalence); Group C statistics based on the regression coefficients and determination coefficients; Group D statistic based on the variance of the deviations from regression ( $s^2d_i$ ).

presented in Table 4. Most of the correlations were significant at the 1% probability level, indicating at least some degree of association among the statistical parameters.

### Correlations among Stability Parameters and Mean Yield

Genotypic mean yield is an important consideration when evaluating and interpreting stability statistics. Mean yield was moderately correlated ( $r = 0.37$ – $0.55$ ) with most parameters (Table 3), but was highly correlated with  $Ad_i$  ( $r = 0.83$ ) and not significantly correlated with four parameters. This indicated that, in general, stability statistics provide information that cannot be gleaned from average yield alone. The strong association between  $Ad_i$  and mean grain yield was expected. By definition,  $Ad_i$  is large for those genotypes whose mean yield consistently exceeds the environment mean (and vice versa). The high correlation suggests that percent adaptability may not provide much more information than mean yield itself.

Parameters that were slightly associated with genotypic mean yields were the linear regression coefficients  $b_i$  and  $b2_i$ . Correlations of similar magnitude were also detected by Langer et al. (1979) and Santos et al. (1982). However, Paroda (1976) concluded that it should be possible to select highly productive cultivars with high, medium or low response indices ( $b_i$ ) due to the low association that he detected. The same idea was defended by Langer et al. (1979). The nonsignificant correlations we observed between mean yield and the regression coefficients  $b'_i$  and  $b1_i$  supports that contention. Conversely, the moderate, but significant, correlations of yield with other regression coefficients,  $b_i$  and  $b2_i$ , do not.

According to Becker and Léon (1988), the correlation frequently detected between genotypic regression coefficients and mean yields may be due to scale effects, and is generally observed when the range in environmental means is small. In our study, there was only about a two-fold range in environmental means.

The near-zero correlation of mean genotypic yields

with genotypic ecovalence values and with the genotypic variances of deviations from regression were consistent with the findings of Langer et al. (1979). The independence of mean yield and ecovalence suggests that ecovalence values and mean yields can be simultaneously used in the selection of high-yielding, stable cultivars.

### Correlations among Stability Parameters within Group

The Group A stability parameters that evaluate stability in terms of the main effect of the genotype, that is, stability is assumed to be a constant phenotypic expression (biological or Type 1 stability—homeostasis). This group includes  $s_i^2$  (Roemer, 1917),  $Ad_i$  (St-Pierre et al., 1967),  $RI_i$  and  $R2_i$  (Langer et al., 1979). The correlations of  $Ad_i$  with the other statistics of this group were low, but significant ( $r = 0.26$ – $0.32$ ). The correlation of  $s_i^2$  and  $RI_i$  was high ( $r = 0.92$ ), whereas the correlation of  $s_i^2$  and  $R2_i$  and that of  $RI_i$  and  $R2_i$  were moderate ( $r = 0.57$ ). The  $s_i^2$  parameter, among the four parameters in the group, is probably the most useful, because it quantitatively reflects the yield of the genotype in all environments.

Group B consists of any parameter that evaluates the stability of genotype via its contribution to the total genotype by environment interaction ( $G \times E$ ). The only parameter that measures this aspect in the present study is  $E_i$  (Wricke, 1965). The correlation of this parameter with the others will be discussed later.

Group C includes the regression coefficients and derived statistics such as the coefficient of determination. Regression coefficients represent a Type 2 stability, that is, a genotype is stable when its response approaches the average response of all tested genotypes ( $b = 1$ ). The coefficient of determination represents the Type 3 stability, that is, the predictability estimated response ( $r^2 = 1$ ).

With one exception, the coefficients of Group C were significantly correlated with each other. The exception involved  $b1_i$  (Silva and Barreto, 1985), which tended to have correlations that were lower in magnitude than the others.

The coefficients  $b'_i$  (Finlay and Wilkinson, 1963) and  $b_i$  (Eberhart and Russell, 1966) were strongly correlated ( $r = 0.76$ ), a result expected from the similarities of their estimation procedures. The coefficient  $b_i$  was independent from  $b1_i$ , but strongly associated with  $b2_i$  (Silva and Barreto, 1985), indicating that the magnitude of  $b_i$  was not influenced much by genotypic yield in unfavorable environments, but was strongly influenced by genotypic yield in the favorable environments. The implication is that  $b_i$  may not be a reliable indicator for the selection of genotypes adapted to poor environments. The logarithmic transformation used for the calculation of  $b'_i$  (Finlay and Wilkinson, 1963) corrected that tendency to some extent, resulting in approximately equal association with responses in the two types of environments.

Coefficients  $b1_i$  and  $b2_i$  exhibited a negative but significant correlation with each other, indicating that the genotypes classed as more yield-responsive genotypes in the highly productive environments tended to be classed as less yield-responsive in the lower-yielding environments. Such association may be an artifact that arises from the estimation procedure for  $b2_i$ , which forces  $b2_i$  to be a direct function of  $b1_i$ . It can also result from the intersection of the two straight line segments in the environment that corresponds to index zero. Cruz et al. (1989) identified such residual negative correlation between the two parameters and considered it to jeopardize the efficiency of the method of Silva and Barreto (1985). They proposed some modifications in the procedure in order to overcome the problem through the discontinuity of the regression function.

The correlations among regression coefficients and coefficients of determination were high and significant. Results indicating independence between such coefficients are reported in the literature (Langer et al., 1979; Santos et al. (1982). Despite these reports, the dependence relationship between coefficients of regression and of determination can be easily noticed in the mathematical expression:

$$r_i^2 = b_i^2 s_f^2 / s_i^2$$

Obviously,  $r_i^2$  is very sensitive to any variation in  $b_i$  because it is directly proportional to the square of the regression coefficient. Such association shows that high responses tend to result in high coefficients of determination and vice versa. So the predictability of the estimated response (Type 3 stability), turns out to be a function of the response itself and the two parameters cannot truly be considered independent.

The correlation between different coefficients of determination ( $r_i^2$  and  $R_i^2$ ) was large and significant, suggesting that both evaluate the same aspects of yield stability. Indeed, inspection of how these are derived from the methods of Eberhart and Russell (1966) and Silva and Barreto (1985), indicates the similarity of the parameters in reflecting the variation of genotype response to environmental variations. These results partially agree with those of Riede and Barreto (1985), Peixoto et al. (1985), Duarte and Zimmermann (1992), and Brasil and Chaves (1992), which found a slight superiority for the method of segmented linear regression.

The D group includes any parameters that measures the predictability of the estimated response (agronomic stability, or Type 3 stability), by measuring the magnitude of deviations from regression. The only statistic that evaluates this in the present study was  $s^2 d_i$ . The correlations of this parameter with other parameters will be discussed later.

### Correlations among Stability Parameters of Different Groups

The correlations of  $Ad_i$  and  $R2_i$  (Group A) with  $E_i$  (Group B) were almost zero, indicating that these parameters evaluate different aspects of yield stability. The statistic  $E_i$  on the other hand, showed significant correlation with  $s_i^2$  and  $RI_i$  (Group A). This shows that a substantial proportion of the phenotypic instability (measured by  $s_i^2$  and  $RI_i$ ) results from the  $G \times E$  sum of squares. Thus, among  $s_i^2$ ,  $RI_i$  and  $E_i$ , one would probably be sufficient as a measure of genotypic stability.

Parameters of Group A were almost always strongly associated with those of the Group C except for  $b1_i$ . Becker (1981) also observed that genotypic regression coefficients and  $s_i^2$  were always strongly associated ( $r_s = 0.99^{**}$  in maize,  $r_s = 0.96^{**}$  in barley, and  $r_s = 0.95^{**}$ , in oats), and recommended the utilization of only one of these as a measure of biological stability. Langer et al. (1979) observed high correlations of  $RI_i$  and  $R2_i$  with  $b_i$  ( $r_s = 0.90^{**}$  and  $r_s = 0.76^{**}$ , respectively), and concluded that genotypes could be selected for their response to environmental improvement using the range of their average yields in the different environments. They noted that this would be particularly useful in the preliminary stages of a breeding program when the breeder has to deal with a large number of genotypes.

Our results also demonstrate that  $s_i^2$ ,  $RI_i$  and  $R2_i$  evaluate stability aspects that are similar to those measured by the regression coefficients  $b'_i$ ,  $b_i$ , and  $b2_i$ . It can be concluded that the regression coefficients, besides characterizing the degree of agronomic stability of the genotype, also evaluate biological stability which is measured by the parameters of the Group A. Thus, the joint utilization of all these parameters is not justifiable.

The absence of correlation among parameters of Group A and  $b1_i$ , supports the view that Group A parameters are not sensitive to the responses in poor environments ( $b1_i$ ), and mainly reflect the genotypic responses to favorable environments ( $b2_i$ ). The  $b1_i$  statistic was generally the most independent parameter of all those measured. This finding supports the utilization of the segmented linear regression method for stability studies.

Correlation among parameters of Group A and Group C coefficients of determination were generally low to moderate, but significant, suggesting that the stability aspect each group measures is somewhat different, but also somewhat overlapping. Simultaneous utilization of these measures could, in some cases, be justified.

Correlations among parameters of Group A and  $s^2 d_i$  (Group D) showed results that were not always consistent. Moderate correlations were found for  $s_i^2$  and  $s^2 d_i$  and for  $RI_i$  and  $s^2 d_i$ , suggesting overlap in their estimation

of stability. On the other hand,  $Ad_i$  and  $R2_i$  exhibited independence in relation to  $s^2d_i$  and probably can be used together for the evaluation of stability.

Groups B and C were generally independent from each other. This shows that estimates such as ecovalence, could be jointly used with the regression coefficients without the risk of measuring the same aspects of yield stability, particularly in those instances where regression coefficients capture only a small fraction of the  $G \times E$  sum of squares.

There was strong association between  $E_i$  (Group B) and  $s^2d_i$  (Group D). This result agrees with those of Langer et al. (1979) in oats ( $r_s = 0.93$ ) and Becker (1981) in maize and barley ( $r_s = 0.94$ ), and also oats ( $r_s = 0.96$ ). Such association is also evident by the similarity of the correlations of  $E_i$  and of  $s^2d_i$  with the other studied stability statistics. Apparently, stability as evaluated by the contribution of each particular genotype to the  $G \times E$  interaction ( $E_i$ ), is not conceptually different from the Type 3 stability as estimated by  $s^2d_i$ . These findings suggest that the Group B statistic  $E_i$  not only reflects a Type 2 stability, as mentioned by Lin et al. (1986), but also reflects a Type 3 stability concept. Consistent with this suggestion is the fact that most of the  $G \times E$  sum of squares was associated with deviations from regression. Finally, this association shows that a joint utilization of  $E_i$  and  $s^2d_i$  for stability studies is not justified.

Among parameters of Groups C and D, it was noticed that all regression coefficients were independent from the variance of deviations from regression ( $s^2d_i$ ) indicating that they can be jointly used in a stability study. Such results agree with those of Paroda (1976), Langer et al. (1979), Santos et al. (1982) and Becker (1981). The mathematical relationship between  $s^2d_i$  and  $b_i$  also provides a similar conclusion after some algebraic manipulation to obtain:

$$s^2d_i = (m - 1)(s_i^2 - b_i^2 s_{ij}^2)/(m - 2)$$

This shows that  $s^2d_i$  has a low sensitivity to the variation in  $b_i$  because  $s^2d_i$  is directly proportional to the difference between phenotypic variance and square of regression coefficient.

The correlations of  $r_i^2$  and  $R_i^2$  with  $s^2d_i$  had moderate magnitudes that were negative, and significant. All three statistics evaluate the predictability of the estimated responses (Type 3 stability). Other researchers have found correlations that were about 0.90 between  $r_i^2$  and  $s^2d_i$

(Langer et al., 1979; Santos et al., 1982; Becker and Léon, 1988).

The lack of correlation of  $s^2d_i$  with most stability parameters, and the strong association between regression coefficients and coefficients of determination, suggest a special analysis for the Type 3 stability indices. Consider, for example, a hypothetical genotype, with linear regression coefficient equal to zero. Because it would have a null value for the coefficient of determination, it would be considered agronomically unstable (by this measure). However, the variance for the deviation from regression would still be  $s_i^2(m - 1)/(m - 2)$  which means that the same genotype could be considered stable or unstable (by this measure), depending upon the magnitude of its phenotypic variance ( $s_i^2$ ). This fact was discussed by Morais (unpublished data, 1980) in rice and by Duarte and Zimmerman (1992) in beans. Genotypes of high stability by  $s^2d_i$  can be considered unstable if evaluated by  $r_i^2$ . This is especially true for those genotypes that have low responses to improving environmental conditions ( $b_i \rightarrow 0$ ). The genotypes L 11090 and LM 30995-0 are practical examples of this (Table 3).

Despite the fact that the coefficient of determination is a relative parameter not dependent on measurement units (Pinthus, 1973; Bilbro and Ray, 1976), the results suggest that  $s^2d_i$  is always more adequate for the evaluation of agronomic stability (Type 3), due to the independence of  $s^2d_i$  relative to the various genotypic regression coefficients. This conclusion is also strengthened by the independence of  $s^2d_i$  relative to genotypic mean yield, a parameter of universal utilization in stability studies. Other advantages of  $s^2d_i$  is its high to moderate correlations with  $E_i$ ,  $s_i^2$  and  $RI_i$ . Apparently,  $s^2d_i$  can be used not only to evaluate the predictability of the estimated response derived from regression procedures, but also evaluate the relative contribution of a genotype to the  $G \times E$  interaction, and indirectly its biological stability.

A global view of the association among the groups of stability statistics is shown in Table 5. This synthesis allows the breeder to make informed choices of the statistics to be used in a stability study. Additionally, it can be said that a good analytical procedure must offer a combination of parameters that give independent and general information about each genotype, meaning that they must evaluate the effects of different gene systems or groups that are involved in the determination of phenotypic stability. Thus, the selected genotypes should show stability that would be given by the largest number of

Table 5. Class summary of the correlations found among genotypic mean yield and four groups of yield stability statistics that were observed in common bean genotypes.

	Variances and ranges	Ecovalence	Regression and determination coefficients	Variances for deviations from regression
Genotypic mean yield	Mostly moderate (one high) correlations	Not correlated	Moderate or near-zero correlations	Not correlated
Variances and ranges		Moderate or near-zero correlations	Moderate to high correlations	Moderate or near-zero correlations
Ecovalence			Near-zero or moderately negative correlations	High correlation
Regression and determination coefficients				Near-zero or moderately negative correlations

such gene groups. The study of phenotypic stability should not be tied to one given method but tailored to the stability type of interest to the individual researcher.

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