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Regression analysis for general adaptation in pearl millet using different environmental indices

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Summary. Regression analyses on grain yield of 20 hybrid and 13 composite varieties of pearl millet (*Pennisetum typhoides* (Burm. S. & H.)) evaluated at 19 sites in India were performed to assess their relative stability and to compare different measures of environmental values. A large portion of the significant genotype × environment interactions was attributed to the non-linear component and deviations mean squares (S^2_{di}) were a very important parameter for selection of stable varieties. The mean grain yield was positively associated with regression coefficients and deviations mean squares. The hybrids MH 31, MH 35, MH 36 and MH 62 and composite populations MP 16, MP 31 and MP 36 possessed general adaptability. The use of dependent, independent and near-independent measures of environmental values has been found to have little influence on the general interpretation of regression analysis in pearl millet.

Key words: *Pennisetum typhoides* (Burm. S. & H.) – Genotype × environment interaction – Regression analysis – Environmental indices

Introduction

The assessment of genotype × environment interactions (G × E) is successfully accomplished by the use of the regression approach of Yates and Cochran (1938); Finlay and Wilkinson (1963); Eberhart and Russell (1966) and Perkins and Jinks (1968). In the regression analysis, mean performance of individual genotypes is regressed on the environmental index measured by the mean performance of all genotypes grown in that environment. The use of this type of dependent environmental index has, however, been criticised by Freeman and Perkins (1971) and comparisons of the use of dependent and independent environmental indices have been made with the fungus *Schizophyllum commune* (Fripp and Caten 1971; Fripp 1972), *Nicotiana rustica* (Perkins and Jinks 1973) and *Avena sativa* (Fatunla and Frey 1976). It has been found that the use of any kind of environmental measures makes little difference on the general conclusions of regression analysis. Parallel studies with *Pennisetum typhoides* along with the relative yield stability of Indian pearl millet varieties are reported in this paper.

Material and methods

Twenty single cross F_1 hybrids and 13 composite populations of pearl millet evaluated in two separate experiments at 19 sites in India in 1980 under the All-India Coordinated Millets Improvement Project (AICMIP) constituted the materials for the present study. At each of the 19 sites, a randomized complete block design with three replicate blocks of 5 m long plots, 6 rows for the hybrid trial and 8 rows for the composite population experiment, was used. A spacing of 50 cm between rows and 10 cm between plants within rows was practised. The grain yield in q/ha was recorded at maturity.

Joint regression analyses were computed following Perkins and Jinks (1968, 1973), and Freeman and Perkins (1971). The sum of squares due to convergence was calculated as described by Mandel (1961) and Eagles et al. (1977). The analyses were performed separately for each of the following three sets based on dependent, independent and near-independent environmental measures, respectively.

a) Dependent measure of environmental values (E_j)

The site means of all entries in a trial were used as the measure of dependent environmental values. Therefore, the environmental values for the hybrid trial were based on 20 hybrids and those for the population trial on 13 populations.

This is the standard method of computing environmental indices (Finlay and Wilkinson 1963).

b) Independent measure of environmental values (Z_j)

The site means for the hybrid trial served as the environmental values for the regression of 13 genotypes in the population trial. Conversely, the site means for the population trial were regarded as the measure of environmental values for the regression of 20 genotypes in the hybrid trial. Thus, the genotypes used for environmental assessment were completely independent from those to be investigated.

c) Near-independent measure of environmental values (X_j)

A common measure of site means was computed as the mean of all the 33 entries, ignoring the trial structure. Each of the 20 hybrids and 13 populations were regressed on these site means irrespective of the trial in which they appeared. Thus, the material used for the environmental assessment was partly the same as that to be investigated.

Table 1. Site mean yield (q/ha) for the 20 hybrids and 13 populations of pearl millet evaluated in hybrid and population trials, respectively

Sr. no.	Site	Mean grain yield (q/ha)	
		Hybrid trial	Population trial
1	Durgapura	7.44	9.46
2	Jodhpur	4.29	3.74
3	Loonkansar	10.63	8.99
4	Chas	4.94	3.12
5	Dhule	28.86	30.34
6	Anand	31.23	29.92
7	Kothara	28.14	18.79
8	Jamnagar	15.04	14.13
9	Bareilly	22.04	22.94
10	Anantpur	8.54	4.55
11	ICRISAT (low fertility)	9.67	11.24
12	ICRISAT (high fertility)	21.83	20.12
13	Guntur	14.77	13.84
14	Vizianagaram	11.41	11.28
15	Coimbatore	23.70	17.82
16	Kovilpatti	11.37	12.77
17	Ludhiana	26.56	25.12
18	Hissar	27.68	30.82
19	Aurangabad	19.91	18.58
	LSD (5%)	1.40	1.37

Results

The range of mean yields of the environments varied from 4.29 q/ha at Jodhpur to 31.23 q/ha at Anand for the hybrid trial and from 3.12 q/ha at Chas to 30.82 q/ha at Hissar for the population trial (Table 1). Thus, locations across India were widely diverse. Further results are presented in two sections. In the first, the stability analysis of the pearl millet genotypes is reported and in the second, the various methods of assessing the environment are compared.

Stability analysis of pearl millet genotypes

Significant variation existed among genotypes (both hybrids and populations) for grain yield and significant mean squares for environments and genotype×environment interactions (Table 2). Both heterogeneity among regressions and deviations mean squares were significant when tested against the pooled error but the former was not significantly greater than the latter. Further, much of the variation in heterogeneity of regressions was due to convergence of regression lines

Table 2. Mean squares from joint regression analyses for pearl millet hybrid and population trials using dependent, independent and near-independent measures of environmental indices

Item	d.f.	Hybrid trial			d.f.	Population trial		
		Dependent	Independent	Near independent		Dependent	Independent	Near independent
Genotypes (G)	19	24.24**	24.24**	24.24**	12	21.95**	21.95**	21.95**
Environments (E)	18	1,566.66*	1,566.66**	1,566.66**	18	966.65**	966.65**	966.65**
Combined regression	1		25,235.57**	27,729.33**	1		16,052.17**	17,218.95**
Residual	17		174.37**	27.68**	17		111.04**	42.40**
G×E	342	12.26**	12.26**	12.26**	216	8.47**	8.47**	8.47**
Heterogeneity of regressions	19	17.16[a]	19.14[a]	18.10[a]	12	12.79[a]	11.60[a]	12.27[a]
Convergence	1	191.24**	188.58**	196.26**	1	51.07*	22.98	40.69
Non-convergence	18	7.48	9.73[a]	8.21[b]	11	9.31[a]	10.57[a]	9.69[a]
Deviations	323	11.94**	11.82**	11.88**	204	8.22**	8.29**	8.25**
Pooled error	988	5.12	5.12	5.12	570	3.19	3.19	3.19

*, ** Significant at the 5% and 1% levels, respectively

[a], [b] Significance at the 5% and 1% levels, respectively, when tested against the pooled error of experiment with additional entries

Table 3. Mean grain yield in q/ha ($\bar{X}_i$), linear regression coefficients (b_i), standard errors of regressions (SE b_i) and deviations mean squares (S^2d_i) computed on dependent environmental indices for individual pearl millet genotypes tested in hybrid and population trials

Genotype	Hybrid trial				Genotype	Population trial			
	$\bar{X}$	b_i	SE b_i	S^2d_i		$\bar{X}_i$	b_i	SE b_i	S^2d_i
MH 31	16.5	1.04	0.07	6.64	MP 15	17.8	1.21**	0.05	3.71
MH 34	18.8	1.18*	0.08	9.00*	MP 16	17.0	1.03	0.06	4.42
MH 35	16.5	1.01	0.06	5.86	MP 17	15.6	1.00	0.08	9.30**
MH 36	17.3	0.98	0.08	8.39+	MP 19	18.0	1.14+	0.07	7.08**
MH 43	15.8	0.88*	0.05	2.89	MP 21	15.3	0.93	0.10	13.16**
MH 49	15.6	0.89	0.09	11.59**	MP 31	16.9	0.95	0.06	4.84
MH 51	16.7	0.93	0.08	9.48*	MP 36	16.2	0.92	0.05	3.99
MH 52	16.8	0.84*	0.07	7.82	MP 37	15.1	0.95	0.09	11.28**
MH 58	16.0	0.80*	0.08	9.93*	MP 38	14.5	1.02	0.08	8.11**
MH 59	18.2	1.15	0.15	31.60**	MP 39	16.0	0.90	0.09	10.25**
MH 60	19.5	1.14	0.09	12.04**	MP 47	15.5	0.86	0.09	10.82**
MH 61	18.0	1.04	0.11	17.88**	MP 53	15.4	1.07	0.06	5.41*
MH 62	17.7	1.09	0.05	3.82	WC-C-75	17.1	1.02	0.07	6.31*
MH 64	17.1	0.96	0.09	12.20**	LSD (5%)	1.1			
MH 65	18.1	1.12	0.13	22.07**					
MH 82	17.5	0.94	0.08	9.13*					
GHB 27	17.1	1.05	0.11	15.72**					
COH 2	19.4	1.08	0.11	15.74**					
BM 46	16.3	0.87*	0.06	5.61					
HB 7	16.8	1.01	0.09	12.50**					
LSD (5%)	1.4								

**, *, + Significant at the 1, 5 and 10% probability level, respectively

at a common point. The convergence indicated a significant correlation of mean yields and regression coefficients which in fact was 0.77 ($P<0.01$) for hybrid and 0.58 ($P<0.05$) for population trials. Thus, a pearl millet variety specifically adapted to low yielding environments that has high mean and low regression should be rare in our materials. This is clear from the stability parameters presented in Table 3 as there existed no millet hybrid or population with exceptionally high mean yield and low regression in our sample. Also, the deviations mean squares were correlated with the mean performance, $r=0.52$ ($P<0.05$) for hybrid and $r=0.60$ ($P<0.05$) for population trials.

Based on the criteria of high mean yield, unit regression and small deviations, (Eberhart and Russell 1966) none of the high yielding hybrids MH 34, MH 59, MH 60, MH 65 and COH 2 possessed general adaptability (Table 2). The hybrids MH 31, MH 35, MH 36 and MH 62 showed mean yields equivalent to the overall trial mean along with unit regression and nonsignificant deviations. These were, therefore, generally adaptable. The hybrid MH 34 with high mean, $b>1.0$ and $S^2_{di}>0$, is specifically suitable for favourable environments. On the other hand, MH 43, MH 52 and BM 46, having $b<1.0$ and $S^2_{di} \simeq 0$, are specifically suitable for unfavourable environments but their mean yields are lower than the overall mean of the experiment. The populations, on the other hand, mostly showed b_i values near unity. The variety MP 15 with high mean, $b>1.0$ and $S^2_{di} \simeq 0$, was specifically suitable for favourable environments. The composite populations MP 16, MP 31 and MP 36 with mean yields equal to the check variety WC-C-75, $b \simeq 1.0$ and $S^2_{di} \simeq 0$, possessed general adaptability.

Comparison of measures of environmental indices

The joint regression analyses for methods (b) and (c) are also presented in Table 2. In both cases, a large part of the environments sum of squares is accounted for by combined regression (Freeman and Perkins 1971). As shown by the environmental residual mean squares, the amount of variation in E_j that is linearly related to Z_j and X_j values, however, decreased as the assessment genotypes became less closely related to the trial genotypes. In general, the use of independent and dependent environmental values had virtually no effect on the overall interpretation of G×E interactions except for the slight significance of the convergence item in method (a) being reduced to non-significance in methods (b) and (c) for the population trial (Table 2).

The estimates of b_i and S^2_{di} values of individual genotypes were computed for each of the three methods separately. The change of environmental measures

Table 4. Rank correlation coefficients between arrays of regression (b_i) and deviations mean squares (S^2_{di}) values computed for each of the 20 hybrids and 13 populations of pearl millet using dependent (a), independent (b) and near-independent (c) measures of environmental values

Trial	Parameter	Method (b)	Method (c)
Hybrids			
Method (a)	b_i	0.99**	0.99**
	S^2_{di}	0.96**	0.98**
Method (b)	b_i		1.00**
	S^2_{di}		0.97**
Populations			
Method (a)	b_i	0.96**	0.98**
	S^2_{di}	0.93**	0.95**
Method (b)	b_i		0.98**
	S^2_{di}		0.95**

** Significant at the 1% level

altered the absolute magnitude of the b_i values but it had very little effect on their relative ranking and significance. The rank correlations between b_i values of different methods presented in Table 4 are all significant. Further, a joint regression analysis was computed for each genotype separately in order to fit a common regression over the three methods. Consistently for all genotypes, a single joint regression at 1 d.f. was significant when tested against the heterogeneity of regressions at 2 d.f., indicating that the regression coefficients were not different over the three measures of environmental values. Deviations mean squares or the standard errors of b_i values, on the other hand, showed an increase as the environmental values became less closely related to the trial genotypes. Clearly, the change of environmental measures may not effect the relative ranking of b_i values but it may influence the precision of comparison of b_i values from one another or from unity.

Discussion

It has been observed that G×E interactions were large for the Indian pearl millet varieties evaluated in the advanced yield trials conducted at 19 locations covering all millet growing regions of the country. In view of this, a strategy of breeding cultivars widely adapted over all locations may be most relevant for the millet growing regions of India. Traditionally, selection for general adaptation in the AICMIP has been attempted by identifying those varieties that have high grain yield over all environments. The present analyses suggest that this procedure would be counter productive since a proportion of the varieties selected would be specifically adapted to high yielding environments. The selection criteria of high mean and $b=1.0$, as suggested by Finlay and Wilkinson (1963), would not be appropriate for these millet varietal data since most of the G×E interaction was not linearly related to environmental indices. Only 8% of the G×E sum of squares in both experiments was accounted for by the G×E (linear) or heterogeneity among regressions and much of the linear component was associated with convergence of regression slopes at a common point.

The relatively low degree of linearity for these data confirms the observations of Eberhart and Russel (1966); Baker (1969); Byth et al. (1976); Eisemann et al. (1977); Jinks and Pooni (1979, and Pooni and Jinks (1980) that G×E interactions are generally not a linear function of the environmental indices. Therefore, for selection of stable millet varieties, the deviations mean squares which describe measurements of unpredictable irregularities in the responses to environments provide the measure of stability and concurrent selection for high mean yield, $b \simeq 1.0$ and $S^2_{di} \simeq 0$, as suggested by Eberhart and Russel (1966), and Perkins and Jinks (1968) would only be rewarding. Furthermore, a high correlation existed between mean yield and regression coefficients, mean yield and deviations mean squares indicating a limited scope for independent manipulation of these properties of the millet varieties. Similar correlations have also been observed by Eberhart and Russel (1966); Perkins and Jinks (1968); Eagles et al. (1977), and Brennan and Byth (1979).

As for the second objective of the assessment of environments, it has been observed that the present findings in pearl millet confirm the results of Fripp (1972); Perkins and Jinks (1973); Fatunla and Frey (1976).

The use of independent and dependent environmental values makes little difference in the regression analysis. In all G×E analyses, independent (Z_j) and near-independent (X_j) environmental measures were highly correlated with dependent (E_j) environmental values. These correlation coefficients were: Z_j vs $E_j=0.95$, X_j vs $E_j=0.99$ for the hybrid trial and Z_j vs $E_j=0.95$, X_j vs $E_j=0.98$ for the population trial. All correlations were significant from zero at the 1% level. This was also confirmed by computing an alternative two-way analysis of variance for the 19 environments and three environmental measures. In this analysis of variance, the environments mean square (MS) at 18 d.f. was 226.42**, the assessment indices MS at 2 d.f. was 5.74, the environments×assessment indices MS at 36 d.f. was 2.14 and the pooled error MS at 1,558 d.f. was 4.41. The interaction item was not significant indicating that any differences that existed between E_j, Z_j and X_j values were consistent over environments. It is thus concluded that regression on to E_j values provides biologically valid information and that complete confidence can be placed on conclusions drawn by plant breeders from the experiments where dependent environmental measures are used.

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