Analysis of Genotype × Environment Interaction for Grain Yield in *Chenopodium* spp.

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Abstract: Twenty-seven germplasm lines of *Chenopodium* spp. were grown in four environments and evaluated for genotype × environment interactions and comparisons between 4 stability parameters viz. Eberhart and Russel's δ_i^2, Shukla's s_i^2, Wricke's W_i^2 and Tai's λ_i were made. Highly significant variance due to environment + (G × E) interaction indicated that genotypes interacted differentially with environments. Shukla's and Wricke's methods gave more or less the same results while large differences occurred between Shukla's and Tai's methods. s_i^2 and W_i^2 exhibited the highest correlation (0.9999**) between themselves. Two diploid and two hexaploid lines, viz. *C. album* cv. Siliguri, *C. album* cv. Chandanbathua, *C. album* PRC 9803 and *C. giganteum* PI 596371, were found to be stable and high yielding.

Keywords: *Chenopodium*; G × E interaction; stability; deviation from regression

Chenopodium spp. have been cultivated for centuries as a grain crop and leafy vegetable for human and animal foodstuff due to high protein content (10–14%) and a balanced amino acid spectrum having high lysine (5.1–6.4%) and methionine (0.4–1.0%) contents (Risi & Galwey 1984; Moerman 1998; Partap *et al.* 1998; Prakash & Pal 1998; Wright *et al.* 2002). It is a crop with a high level of resistance to some predominant adverse factors such as soil salinity, drought, frost, diseases and pests (Wilson 1990; Jacobsen *et al.* 2003). The immense nutritional importance coupled with the ability to grow in stress environments makes *Chenopodium* a potential crop for diversification of agricultural systems on degraded and marginal lands.

Genotypic evaluation of a crop requires to conduct yield trials with many genotypes in multiple sites and/or years. Genotypes performing consistently over a wide range of environments are considered stable. Others showing considerable genotype × environment interaction (GEI) effects are not suited for diverse environments (Thillainathan & Fernandez 2002) and severely limit the selection of superior genotypes (Zobel 1990). Plant breeders continuously strive to broaden the genetic base of a crop to prevent its vulnerability to changing environments. The study of GEI provides information about the suitability of genotypes over diverse agro-climatic conditions.

Few reports on GEI and stability analysis in *Chenopodium* were published (Risi & Galwey 1991; Jacobsen *et al.* 1996; Jacobsen 1998) and they are confined to the study of a single species *C. quinoa*. Studies on many other species of the genus, especially *C. album*, are entirely missing. The present investigation was therefore undertaken to fill this gap by ascertaining the extent of GEI effects in *Chenopodium* and to select relatively stable genotypes for a future breeding programme.

MATERIAL AND METHODS

Experimental site and material. The experimental material consisted of 27 germplasm lines of *Chenopodium* comprising 16 lines of *C. album*,

3 lines of *C. giganteum*, 1 line each of *C. bushianum*, *C. amaranticolor*, *C. strictum*, *C. ficifolium*, *C. botrys*, *C. opulifolium*, *C. murale* and 2 selections from 2 separate cross progenies (Table 1). The material was diverse in terms of both the ploidy level and the distributional range. The material was evaluated in a randomised block design with three replications in four environments (2000–2001, 2001–2002, 2002–2003 and 2003–2004) in the experimental field of National Botanical Research Institute, Lucknow. The experimental site is situated at a height of 120 m above sea level at 26.5°N latitude and 80.5°E longitude. Data was recorded for grain yield (g/plant) on 5 randomly selected plants of each replication and further analysis was done on mean data across the lines.

Statistical analysis. A number of statistical models are available for evaluating the yield stability of a genotype in yield trials (Plaisted & Peterson 1959; Wricke 1962; Finlay & Wilkinson 1963; Eberhart & Russel 1966; Tai 1971; Shukla 1972; Shafii & Price 1998). The stability measures are classified according to whether they are based on GEI component or regression on environmen-

Table 1. *Chenopodium* germplasm lines, their origin, ploidy level and chromosome number

Sample No.	Germplasm line	Origin	Ploidy level	Chromosome No.
1.	*C. album* PRC 9801	Himachal Pradesh, India	6*x*	54
2.	*C. album* PRC 9803	Himachal Pradesh, India	6*x*	54
3.	*C. album* PRC 9804	Himachal Pradesh, India	6*x*	54
4.	*C. album* PRC 9802	Himachal Pradesh, India	6*x*	54
5.	*C. album* IC 107297	Himachal Pradesh, India	6*x*	54
6.	*C. album* IC 107296	Himachal Pradesh, India	6*x*	54
7.	*C. album* cv. Iowa	Iowa, USA	6*x*	54
8.	*C. album* cv. Czech	Czech Republic	6*x*	54
9.	*C. album* 'local'	Lucknow, India	6*x*	54
10.	*C. album* CHEN 60/76	Belgium*	6*x*	54
11.	*C. album* CHEN 85/82	Libyan Arab Jamahiriya*	6*x*	54
12.	*C. album* PI 605700	Michigan, USA**	6*x*	54
13.	*C. album* cv. Mexico	Mexico	4*x*	36
14.	*C. album* cv. Siliguri	Siliguri, India	2*x*	18
15.	*C. album* cv. Chandanbathua	India	2*x*	18
16.	*C. album* 'local red'	Lucknow, India	2*x*	18
17.	*C. giganteum* PI 596371	Oklahoma, USA**	6*x*	54
18.	*C. giganteum* PI 596372	California, USA**	6*x*	54
19.	*C. bushianum* cv. Ames 22376	Illinois, USA**	6*x*	54
20.	*C. giganteum* 'local'	Himachal Pradesh, India	6*x*	54
21.	*C. strictum* CHEN 47/79	unknown*	6*x*	54
22.	*C. opulifolium* CHEN 43/96	unknown*	6*x*	54
23.	*C. botrys* CHEN 94/96	unknown*	2*x*	18
24.	*C. ficifolium* CHEN 47/78	unknown*	2*x*	18
25.	*C. murale* cv. Local	Lucknow, India	2*x*	18
26.	*C. album* x *C. quinoa* (colchiploid)	hybrid	6*x*	54
27	*C. album* × *C. album* cv. Siliguri	hybrid	2*x*	18

Source: *IPK Gatersleben, Germany; **USDA

tal mean. The present study is based mainly on Eberhart and Russel's joint regression analysis and comparisons between 4 stability parameters, viz. Eberhart and Russel's δ_i^2, Shukla's s_i^2, Wricke's W_i^2 and Tai's λ_i, were made. The aim is to compare different stability parameters and suggest relatively stable lines of *Chenopodium* for further use in breeding programmes. Eberhart and Russel's (1966) deviation from regression parameter δ_i^2 was calculated as follows:

$$\delta_i^2 = [\sum_j \delta_{ij}^2/(s-2)] - (S_e^2/r)$$

where: δ_i^2 – variance due to deviation from regression
s – number of environments
S_e^2 – estimate of pooled error

Wricke's (1962) ecovalence (W_i^2) evaluates stability on the basis of the contribution of each genotype to the total GEI sum of squares and is given by the following formula:

$$W_i^2 = \sum_j (X_{ij} - \bar{X}_j - \bar{X}_i. + \bar{X}_{..})^2$$

where: X_{ij} – mean of genotype i in environment j
$\bar{X}_j$ – mean yield of genotypes across environments
$\bar{X}_i$ – environment mean
$\bar{X}_{..}$ – overall mean

Shukla's (1972) s_i^2 uses the variance of a genotype across environments as its measure of stability. s_i^2 is calculated using the following formula:

$$s_i^2 = t/(t-2) \times (s-2)\,[S_i - \sum_i S_i/t(t-1)]$$

where: t – number of genotypes
s – number of environments
S_i – stability variance

Tai's λ_I (1971) measures the deviation from the linear response in terms of the magnitude of error variance and is given by:

$$\lambda_I = MSD_i/(m-1) \times (MSE/mr)$$

where: MSD_i – mean square deviation from regression
m – number of genotypes
MSE – mean square error
r – number of replications

For grouping the germplasm lines, we used the method according to Chandler *et al*. (1991). Germplasm lines having the yield above the grand mean and $\beta_i \leq 1$ were termed stable and put in Group I. Lines with the yield above the grand mean and $\beta_i > 1$ were considered unstable and adapted to favourable environments. They were placed in Group II. Others with the yield below the grand mean and $\beta_i < 1$ were considered stable but low-yielding and were categorised into Group III. Group IV comprised unstable and low-yielding lines having the below-average yield and $\beta_i > 1$. Apart from this the significant values of β_i and δ_i^2 were also taken into account.

RESULTS AND DISCUSSION

The analysis of variance for stability revealed highly significant differences between the geno-

Table 2. ANOVA for stability of 27 germplasm lines over 4 environments

Source of variations	df	Sum of squares	Mean squares
Replications within environments	8	40.04	5.00
Germplasm lines	26	18 859.36	725.36**
Environment + (germplasm lines × environment)	81	1 681.26	20.75**
Environments	3	443.65	147.88**
Germplasm lines × environment	78	1 237.61	15.86**
Environments (Lin.)	1	443.65	443.65**
Germplasm lines × environment (Lin.)	26	946.87	36.41**
Pooled deviation	54	290.74	5.38**
Pooled error	208	640.51	3.07
Total	107	20 540.63	191.96

types (Table 2), which suggested that the germplasm lines differed considerably with respect to yield performance. Highly significant variance due to environment + (G × E) interaction indicated that genotypes interacted differentially with environments. The G × E interaction was further partitioned into linear and non-linear components. The G × E (linear) as well as pool deviation mean squares were found significant indicating the presence of both predictable and non-predictable components. The importance of both linear and non-linear sensitivity for the expression of the trait was thus evident.

The grain yield of 27 genotypes in 4 separate environments and their means are given in Tables 3 and 4. All the indigenous genotypes except *C. album* cv. Local red, C. *album* cv. Local and *C. murale* cv. Local gave above-average yield performance in all the 4 environments as well as on overall mean basis. The yield performance of the introduced lines was however variable. *C. album* PI 605700 was the most promising germplasm line in this

Table 3. Grain yield/plant for 27 germplasm lines of *Chenopodium* over 4 environments

Genotypes	Environment 1	Environment 2	Environment 3	Environment 4
C. album PRC 9801	30.21	24.30	24.85	25.93
C. album PRC 9803	26.95	23.16	22.67	24.93
C. album PRC 9804	30.56	18.06	25.57	26.26
C. album PRC 9802	46.13	30.03	28.46	32.90
C. album IC 107297	64.11	43.03	33.35	44.86
C. album IC 107296	41.95	28.73	28.62	32.20
C. album cv. Iowa	21.00	20.70	20.27	23.53
C. album cv. Czech	3.83	7.23	8.45	5.13
C. album 'local'	22.00	18.26	11.91	20.16
C. album CHEN 60/76	5.43	7.43	10.06	7.20
C. album CHEN 85/82	5.96	6.10	7.71	6.06
C. album PI 605700	59.33	52.73	44.99	47.30
C. album cv. Mexico	23.85	19.36	14.67	21.80
C. album cv. Siliguri	26.50	30.43	35.22	27.30
C. album cv. Chandanbathua	26.41	25.53	23.20	25.56
C. album 'local red'	20.16	16.46	11.36	16.16
C. giganteum PI 596371	23.96	24.50	24.07	24.76
C. giganteum PI 596372	35.80	25.00	23.61	27.93
C. bushianum cv. Ames 22376	10.30	17.20	15.53	12.16
C. giganteum 'local'	46.80	41.61	32.99	38.60
C. strictum CHEN 47/79	14.23	17.46	8.46	12.96
C. opulifolium CHEN 43/96	23.20	15.36	14.96	18.83
C. botrys CHEN 94/96	5.76	4.32	7.55	6.43
C. ficifolium CHEN 47/78	4.02	3.95	4.33	4.36
C. murale cv. Local	11.83	5.20	8.03	11.36
C. album × *C. quinoa* (colchiploid)	5.53	2.81	2.19	2.83
C. album × *C. album* cv. Siliguri	49.06	38.56	45.76	46.56
Mean ± S.E.	25.36 ± 3.29	21.01 ± 2.49	19.95 ± 2.29	22.00 ± 2.50

group giving the highest yield in environment 2 (52.73 g/plant) and environment 4 (47.30 g/plant) and on overall mean basis (51.09 g/plant). All the lines of *C. giganteum* gave high grain yield in 3 environments and on overall mean basis. The hybrid *C. album* × *C. album* cv. Siliguri gave very high yields in all the 4 environments, while the yield performance of another hybrid, *C. album* × *C. quinoa* (colchiploid) was poor in all the environments. Five introduced lines, namely *C. album* CHEN 60/76, *C. album* CHEN 85/82, *C. album* cv. Czech, *C. ficifolium* CHEN 47/78 and *C. botrys* CHEN 94/96, also gave very poor yield in all the environments. Thus, 75.00% of the indigenous and only 23.07% of the introduced lines were high yielding.

Yield trials conducted with many genotypes grown in multiple site/years form the basis of comparative genotypic evaluation. Consistent

Table 4. Mean yield, β_i, δ_i^2 and categorisation of 27 germplasm lines of *Chenopodium*

Genotypes	Parameter			Inference		
	mean	β_i	δ_i^2	yield	stability	category
C. album PRC 9801	26.32 ± 1.33	1.10	–2.32	high	unstable	II
C. album PRC 9803	24.42 ± 0.97	0.81	–2.89	high	stable	I
C. album PRC 9804	25.11 ± 2.59	1.48	19.30**	high	unstable	II
C. album PRC 9802	34.38 ± 4.02	3.40**	–1.11	high	unstable	II
C. album IC 107297	46.33 ± 6.43	5.45**	1.48	high	unstable	II
C. album IC 107296	32.87 ± 3.13	2.63	–1.15	high	unstable	II
C. album cv. Iowa	21.37 ± 0.73	0.10	0.00	low	stable	III
C. album cv. Czech	6.16 ± 1.03	–0.82**	–2.31	low	stable	III
C. album 'local'	18.08 ± 2.19	1.55	5.79	low	unstable	IV
C. album CHEN 60/76	7.53 ± 0.95	–0.73**	–2.16	low	stable	III
C. album CHEN 85/82	6.45 ± 0.41	–0.23**	–2.55	low	stable	III
C. album PI 605700	51.08 ± 3.19	2.34	12.66**	high	unstable	II
C. album cv. Mexico	19.92 ± 1.97	1.49	2.01	low	unstable	IV
C. album cv. Siliguri	29.86 ± 1.97	–1.38	4.44	high	stable	I
C. album cv. Chandanbathua	25.17 ± 0.68	0.47	–2.16	high	stable	I
C. album 'local red'	16.03 ± 1.80	1.40	0.27	low	unstable	IV
C. giganteum PI 596371	24.32 ± 0.18	–0.05**	–2.96	high	stable	I
C. giganteum PI 596372	28.08 ± 2.72	2.32	–2.85	high	unstable	II
C. bushianum cv. Ames 22376	13.79 ± 1.56	–1.13	0.99	low	stable	III
C. giganteum 'local'	40.00 ± 2.88	2.16	8.19**	high	unstable	II
C. strictum CHEN 47/79	13.27 ± 1.86	0.54	15.27**	low	stable	III
C. opulifolium CHEN 43/96	18.08 ± 1.91	1.59	–2.20	low	stable	IV
C. botrys CHEN 94/96	6.01 ± 0.67	–0.14	–0.58	low	stable	III
C. ficifolium CHEN 47/78	4.16 ± 0.10	–0.03**	–3.09	low	stable	III
C. murale cv. Local	9.10 ± 1.55	0.92	4.29	low	stable	III
C. album x *C. quinoa* (colchiploid)	3.34 ± 0.74	0.62	–3.01	low	stable	III
C. album x *C. album* cv. Siliguri	44.98 ± 2.25	1.12	16.98**	high	unstable	II
Mean ± S.E.	22.08 ± 2.59	–	–	–	–	–

performances across different sites and/or years are referred to as yield stability (Thillainathan & Fernandez 2002). Stability can be assessed in a number of ways. Finlay and Wilkinson (1963) considered the linear regression slope as a measure of stability. Shukla's (1972) stability variance and Wricke's (1962) ecovalence concept are other stability measures used but both give similar results for the ranking of genotypes. Tai (1971) partitioned the GE (ge_{ij}) interaction term into the components: linear response to environmental effects ($\propto_i$) and deviation from linear response (λ_i). However, Eberhart and Russell's (1966) model is one of the most widely used stability models that considers both linear and non-linear components of GE interaction in judging the stability of genotypes. In this model a variety with high mean, regression coefficient $\beta_i = 1$ and deviation not significantly different from zero ($\delta_i^2 = 0$) is said to be stable.

Group I comprised 4 high-yielding stable lines, two of which were diploids and two hexaploids

Table 5. Comparison of 4 stability parameters for each germplasm line

Genotype	Eberhart and Russel's δ_i^2	Tai's λ_i	Shukla's s_i^2	Wricke's W_i^2
C. album PRC 9801	–2.32	0.18	0.43	1.18
C. album PRC 9803	–2.89	0.05	0.17	1.09
C. album PRC 9804	19.30**	4.72**	17.32**	48.70**
C. album PRC 9802	–1.11	0.35	35.36**	98.83**
C. album IC 107297	1.48	0.60	120.39**	335.01**
C. album IC 107296	–1.15	0.37	17.03**	47.91**
C. album cv. Iowa	0.00	0.74	6.83**	19.59**
C. album cv. Czech	–2.31	0.21	20.10**	56.45**
C. album 'local'	5.79	1.86	8.07**	23.02**
C. album CHEN 60/76	–2.16	0.25	18.38**	51.67**
C. album CHEN 85/82	–2.55	0.14	9.25**	26.29**
C. album PI 605700	12.66**	3.05	21.90**	61.44**
C. album cv. Mexico	2.01	1.08	4.92**	14.28**
C. album cv. Siliguri	4.44	2.02	39.02**	108.98**
C. album cv. Chandanbathua	–2.16	0.22	2.10	6.43
C. album 'local red'	0.27	0.72	3.20**	9.48**
C. giganteum PI 596371	–2.96	0.04	6.47**	18.58**
C. giganteum PI 596372	–2.85	0.05	10.31**	29.25**
C. bushianum cv. Ames 22376	0.99	1.08	29.73**	83.18**
C. giganteum 'local'	8.19**	2.23	16.00**	45.05**
C. strictum CHEN 47/79	15.27**	4.21**	14.28**	40.27**
C. opulifolium CHEN 43/96	–2.20	0.19	2.58	7.76
C. botrys CHEN 94/96	–0.57	0.62	9.32**	26.51**
C. ficifolium CHEN 47/78	–3.09	0.01	6.19**	17.80**
C. murale cv. Local	4.28	1.64	5.17**	14.97**
C. album × *C. quinoa* (colchiploid)	–3.01	0.03	0.72	2.61
C. album × *C. album* cv. Siliguri	16.98**	4.37**	14.37**	40.51**

(Table 4). Likewise 4 germplasm lines were included in Group IV that were unpromising in terms of both yield and stability. Table 4 shows that a majority of germplasm lines clustered in Groups II and III (9 and 10 lines, respectively). The 9 lines of Group II were high yielding, had non-significant $\beta_i > 1$ and non-significant deviation from regression suggesting that they are adapted to favourable environments and would perform well when such an environment is provided. Thus, only 48.15% of the germplasm lines under study were stable, which is surprising considering the generalised view that the genus is relatively stable. These results were also supported by other genotypic stability measures like Wricke's ecovalence (W_i^2) and Shukla's s_i^2 values (Table 5). Both these measures were categorised in Type II stability by Lin *et al*. (1986) where a genotype is considered to be stable if its response to environments is parallel to the mean response of all the genotypes in the trial. Wricke's ecovalence (W_i^2) values ranged from 1.09 for *C. album* PRC 9803 to 335.01 for *C. album* IC 107297 (Table 5). Only 5 out of the 27 lines showed non-significant W_i^2 values. A significant W_i^2 value is considered as an indicator of low stability, while $W_i^2 = 0$ gives the greatest stability. Thus, only 18.52% of the lines were found to be stable.

Shukla (1972) measured stability on the basis of the contribution of a genotype to the GEI sum of squares and gave the concept of adjusted stability variance (s_i^2) which is obtained by removing the linear effect of environment from GEI and partitioning the remainder of GEI variance into a component (s_i^2). Shukla's s_i^2 values ranged from 0.17 for PRC 9803 to 120.39 for *C. album* IC 107297 (Table 5). Shukla's model gave the same results as Wricke's model and this supports Becker and Leon's (1988) observation that both Shukla's stability variance and Wricke's ecovalence give the same results for the ranking of genotypes. However, Tai's model gave very different results. Tai's λ_i measures stability using the deviation from the linear response (λ_i) in terms of the magnitude of error variance. Tai's λ_i values ranged from 0.03–4.72 and were significant for 3 lines, viz *C. album* PRC 9804, *C. strictum* CHEN 47/79 and *C. album* × *C. album* cv. Siliguri Thus, Tai's model gave 88.89% of the lines as stable.

This discrepancy in the results between Tai's model and Shukla's model is due to a number of reasons. Firstly, the number of lines used in the present study is large and Tai's model is preferred only when the number of genotypes is smaller. Secondly, Shukla's method is based on interaction totals while Tai uses interaction mean for analysis. But, the major reason for disagreement between λ_i and s_i^2 is the method of their testing which was explained earlier by Fernandez (1991). The significance of s_i^2 is tested by an $F_{0.05}$ test with $(n - 1)$ and $nm\ (r - 1)$ d*f* while the significance of λ_i is derived by an $F_{0.025}$ value with $(n - 2)$ and $n(m - 1)\ (r - 1)$ as numerator and denominator, respectively. Here m, n and r correspond to the number of genotypes, environments and replications, respectively. Thus, the F value ($F_{0.05}$ and $F_{0.025}$) as well as the numerator $df\ (n - 1)$ and $df\ (n - 2)$ used by both models leads to this contradiction.

The correlation coefficients for grain yield were significant for all the 4 parameters studied (Table 6). Within the parameters, the highest correlation was present between s_i^2 and W_i^2 (0.9999**) and between δ_i^2 and λ_i (0.9942**). Correlations between the other pairs of combinations were insignificant. Such a high value of correlation coefficient between s_i^2 and W_i^2 was also reported in other crops, e.g. in *Panicum* (Fuentes & Talaiferro 2002).

After comparison between all the stability parameters, four lines, viz. *C. album* PRC 9803, *C. al-*

Table 6. Correlation coefficients between grain yield and stability parameters

Variable	Yield	δ_i^2	λ_1	s_i^2	W_i^2
Yield	1.0000	0.4172*	0.3627*	0.4559**	0.4557**
δ_i^2		1.0000	0.9942**	0.1067	0.1069
λ_i			1.0000	0.0672	0.0673
s_i^2				1.0000	0.9999**
W_i^2					1.0000

bum cv. Siliguri, *C. album* cv. Chandanbathua and *C. giganteum* PI 596371, were found to be stable and high yielding. These lines demonstrated high yield performance (22.67, 35.22, 23.20 and 24.07 g per plant, respectively) even in the poorest environment (Environment 3, mean yield – 19.95 g/plant). These lines could serve as potential parents for future selection programmes in *Chenopodium*.

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Souhrn

Bhargava A., Shukla S., Ohri D. (2005): **Analýza interakce genotypu s prostředím ve výnosu zrna u** *Chenopodium* spp. Czech J. Genet. Plant Breed., **41**: 64–72.

U 27 linií *Chenopodium* spp., pěstovaných ve čtyřech typech prostředí, byly hodnoceny interakce genotypu s prostředím a porovnávány údaje čtyř parametrů stability: Eberhart a Russel δ_i^2, Shukla s_i^2, Wricke W_i^2 a Tai λ_i. Vysoká významnost složky rozptylu vlivem prostředí + interakce genotypu s prostředím indikovala, že genotypy rozdílně reagovaly na prostředí. Metody Shukla a Wricke poskytovaly obdobné výsledky, avšak výrazně rozdílné výsledky byly zjištěny mezi použitím metod Shukla a Tai. Nejtěsnější korelace (0,9999**) byla zjištěna mezi parametry s_i^2 a W_i^2. Dvě diploidní a dvě hexaploidní linie (*Ch. album* cv. Siliguri, *Ch. album* cv. Chandanbathua, *Ch. album* PCR 9803 a *Ch. giganteum* PI 596371) vykázaly výnosovou stabilitu a vysoký výnos.

Klíčová slova: *Chenopodium*; interakce G × E; stabilita; odchylky od regrese

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