DOI: http://dx.doi.org/10.22092/cbj.2011.100360

Repeatability and relationships among parametric and non-parametric yield stability measures in safflower (*Carthamus tinctorius* L.) genotypes

S. S. Pourdad

Dryland Agricultural Research Institute, Sararoud, Kermanshah, Iran.
E-mail address: sspourdad@yahoo.com

Received: September 2010

ABSTRACT

Pourdad, S. S. 2011. Repeatability and relationships among parametric and non-parametric yield stability measures in safflower (*Carthamus tinctorius* L.) genotypes. **Crop Breeding Journal 1(2): 109-118.**

The occurrence of genotype × environment (GE) interaction has led to the development of several stability parameters that can be used to estimate the stability of cultivar performance. Repeatability of 20 parametric and non-parametric stability measures across years and yield subsets as well as their association with mean seed yield and interrelationship among them in safflower (*Carthamus tinctorius* L.) were studied. Seed yields of 14 safflower advanced breeding lines were evaluated in 46 environments (10 locations in the 2000-2005 growing seasons, with some missing combinations) under rainfed conditions in semi-arid areas of Iran. A wide range of stability statistics, including 12 parametric and 8 non-parametric stability measures, were calculated for seed yield. The repeatability of stability measures, the interrelationships among them and their association with mean yield were estimated using Spearman's rank correlation over environments. A combined analysis of variance revealed highly significant environmental and G × E effects over all years and yield subsets. The AMMI analysis showed that in most of the years and subsets, three first interaction principal component axes (IPCA1, IPCA2 and IPCA3) explained G × E interaction. Rank correlation between stability measures and mean yield was repeatable for four parametric measures including superiority index (P_i), geometric adaptability index (GAI), regression coefficient (b_i) and environmental variance (S^2_{xi}), as well as five non-parametric stability statistics including Nassar and Huehn (1987) stability statistics ($S_i^{(3)}$, $S_i^{(6)}$) and Thennarasu (1995) measures ($NP_i^{(2)}$, $NP_i^{(3)}$ and $NP_i^{(4)}$). Rank correlations among stability measures showed that non-parametric statistics were more correlated than parametric statistics over years and yield subsets. For example; $S_i^{(3)}$ can be used instead of $S_i^{(2)}$, $S_i^{(6)}$, $NP_i^{(1)}$, $NP_i^{(2)}$ and $NP_i^{(3)}$. Repeatability of the stability measures obtained in consecutive single years was low but moderate for b_i and GAI in subsets, and highly repeatable for P_i, GAI, $NP_i^{(3)}$ and $NP_i^{(2)}$ in year/subsets versus the remaining environments. Superiority measure (P_i) and geometric adaptability index (GAI), along with two Thennarasu non-parametric stability measures ($NP_i^{(2)}$ and $NP_i^{(3)}$), displayed strong rank correlations with seed yield, and high repeatability. Therefore, these statistics can be used simultaneously with seed yield to select genotypes with high yield and high yield stability in safflower breeding programs.

Key words: rank correlation, safflower, G× E interaction, adaptability index, yield stability statistics

INTRODUCTION

Safflower (*Carthamus tinctorius* L.), which originated in the eastern Mediterranean region, is suitable for cropping systems in the drylands of Iran that receive winter and spring rainfall (Pourdad and Beg, 2003). It is also suitable for semi-arid, rainfed Mediterranean areas (Yau, 2005). Safflower is a multi-purpose crop known to be drought tolerant due to its long deep roots. Drought and terminal heat stresses adversely affect yield performance of crops in dryland regions. In addition, in multi-environment trials (MET), these stresses frequently induce genotype × environment interactions (G × E) that reduce the efficiency of variety selection and recommendation. When genotypic performance in different environments is extremely different, G×E becomes a major challenge to genetic improvement programs (Zobel and Talbert, 1984). If cultivars are being selected for a large group of environments, stability and mean yield across all environments are more important than yield for specific environments (Piepho, 1996). A variety or genotype is considered to be more stable if it has high mean yield but a low degree of yield variability when grown over diverse environments (Arshad *et al.*, 2003).

Many stability measures and statistics can be used to estimate the stability of genotype performance. Considering the final goal of the breeding program and the trait of interest, two concepts of stability can be introduced: the biological and the agronomic concepts (Becker, 1981), also known as the static and dynamic concepts. Huehn (1996) described two major G × E stability approaches: the commonly used parametric approach that relies on distributional assumptions, and the non-parametric approach, which needs no assumptions.

Parametric methods can be divided into univariate and multivariate stability statistics. Joint regression is the most popular univariate approach and includes: a regression coefficient (b_i) and variance of deviation from regression (S^2_{di}) (Eberhart and Russell, 1966). According to the joint regression model, a stable genotype is one with b=1 and $S^2_{di}=0$. Environmental variance (S^2_{xi}) is a measure of the static concept of stability, and a genotype with minimum S^2_{xi} in different environments is considered stable (Lin *et al.*, 1986; Becker and Leon, 1988). The contribution of a genotype to the sum of squares of interactions, which is termed ecovalence (W^2_i), can be used as a measure of its stability (Wricke, 1962). The highest stability is when $W^2_i=0$. Shukla's (1972) stability variance and W^2_i give the same results when ranking genotypes (Becker and Leon, 1988). Francis and Kannenberg (1978) measured stability by combining a coefficient of variation (CVi) and mean yield. Genotypes with low CVi and high mean yield were considered most desirable. The superiority measure (P_i) is the mean square of the distance between genotype i and the genotype with the maximum yield within each environment (Lin and Binns, 1988). Genotypes with small P_i values are desirable.

$$P_i = \frac{\sum_{j=1}^{m}\left(X_{ij} - M_j\right)^2}{2E}$$

where X_{ij} is the yield of genotype i in environment j, M_j is the genotype with maximum yield in environment j and E is the number of environments. Kataoka (1963) proposed a yield reliability index (I_i) for economic analysis. The relative importance attributed to yield stability in the index depends on the average level of risk aversion of farmers in the target region or sub-region. In particular, Kataoka's index can be used for estimating, on the basis of yield distribution values observed across test environments (cultivar recommendation) or selection of environments (breeding), the lowest yield expected for a given genotype and a specified probability of a negative event (Eskridge, 1990). *P* values may vary between 0.95 for subsistence agriculture in unfavorable cropping systems to 0.70 for modern agriculture in most favorable regions. In general, the index value (*I*) for the genotype *i* is: $I_i = m_i - Z_{(P)} S_i$

where m_i = mean yield, S_i = square root of the environmental variance, and $Z_{(P)}$ = percentile from the standard normal distribution for which the cumulative distribution function reaches the value *P*. $Z_{(P)}$ can assume the following values depending on the chosen *P* level: 0.675 for *P* = 0.75; 0.840 for *P* = 0.80; 1.040 for *P* = 0.85; 1.280 for *P* = 0.90; and 1.645 for *P* = 0.95. The geometric mean can be used as a measure of the adaptability of a genotype, also known as geometric adaptability index (GAI), and is calculated as $GAI = \sqrt[E]{(\bar{X}_{1.})(\bar{X}_{2.})....(\bar{X}_{I.})}$

where $\bar{X}_{1.}$, $\bar{X}_{2.}$ and $\bar{X}_{I.}$ are the mean yields of the first, second and *i*th genotypes across environments and E is the number of environments. Genotypes with high GAI are desirable.

Additive Main effects and Multiplicative Interaction (AMMI) (Crossa, 1990; Gauch, 1992) is gaining popularity and is currently the main alternative multivariate approach to joint regression analysis in many breeding programs (Annicchiarico, 1997). More recently, Purchase *et al.* (2000) developed the AMMI stability value (ASV) based on the AMMI model's IPCA1 and IPCA2 scores for each genotype. ASV is in effect the distance from the coordinate point to the origin in a two dimensional scattergram of IPCA1 scores against IPCA2 scores. The genotypes with the highest ASV values are considered the most stable. The ASV values are calculated as follows:

$$ASV = \sqrt{\left[\frac{SS_{IPCA1}}{SS_{IPCA2}}(IPCA1_{Score})\right]^2 + (IPCA2_{Score})^2}$$

where SS_{IPCA} = sum of squares of IPCA.

Non-parametric measures developed in the field of medicine can be applied to GEI in METs (Truberg and Huehn, 2000). Nassar and Huehn (1987) and Huehn (1979) proposed four non-parametric stability statistics ($S_i^{(1)}, S_i^{(2)}, S_i^{(3)}$ and $S_i^{(6)}$) which are based on yield rank of genotypes in each environment as below:

$$S_i^{(1)} = 2\sum_{j=1}^{m-1}\sum_{(j'=j+1)}^{m}\left|r_{ij} - r_{ij'}\right| \Big/ \left[m(m-1)\right]$$

$$S_i^{(2)} = \frac{\sum_{j=1}^{m}(r_{ij} - \bar{r}_{i.})^2}{m-1}$$

$$S_i^{(3)} = \frac{\sum_{j=1}^{m}(r_{ij} - \bar{r}_{i.})^2}{\bar{r}_{i.}}$$

$$S_i^{(6)} = \frac{\sum_{j=1}^{m} |r_{ij} - \bar{r}_{i.}|}{\bar{r}_{i.}}$$

For two-way data with l genotypes and m environments, we denote r_{ij} as the rank of the i[th] genotype in the j[th] environment, and $\bar{r}_{i.} = \sum_j \frac{r_{ij}}{m}$.

Thennarasu (1995) proposed four non-parametric statistics, $NP_i^{(1)}$, $NP_i^{(2)}$, $NP_i^{(3)}$ and $NP_i^{(4)}$, based on ranks of adjusted means of the genotypes in each environment. The adjusted means calculated from adjusted values ($X_{ij}^* = X_{ij} - \bar{X}_{i.} + \bar{X}_{..}$), where X_{ij} is the performance of the *i*th genotype in the *j*th environment, $\bar{X}_{i.}$ is the mean performance of the *i*th genotype and $\bar{X}_{..}$ is the overall mean across environments. These statistics are calculated as follows:

$$NP_i^{(1)} = \frac{1}{m} \sum_{j=1}^{m} |r_{ij}^* - M_{di}^*|$$

$$NP_i^{(2)} = \frac{1}{m} \left(\sum_{j=1}^{m} |r_{ij}^* - M_{di}^*| / M_{di} \right)$$

$$NP_i^{(3)} = \frac{\sqrt{\sum_{j=1}^{m} \left(r_{ij}^* - \bar{r}_{i.}^*\right)^2 / m}}{\bar{r}_{i.}}$$

$$NP_i^{(4)} = \frac{2}{m(m-1)} \left[\sum_{j=1}^{m-1} \sum_{(j'=j+1)}^{m} |r_{ij}^* - r_{ij'}^*| / \bar{r}_{i.} \right]$$

where r^*_{ij} is the rank of adjusted values (X^*_{ij}), M^*_{di} and $\bar{r}*_{ij}$ are the median and mean ranks based on adjusted values, respectively, while M_{di} and $\bar{r}_{ij}$ are the median and mean ranks based on original values.

Rank correlation is an important and useful tool for studying the statistical relations among stability parameters, finding the best method to use as an alternative for other methods, and eliminating similar parameters.

There are few studies on yield stability of safflower (Rangarao and Ramachandra,1979; Narkhede *et al.,* 1984; Yau and Hunt, 1998; Elfadl *et al.,* 2005; Mahasi *et al.*, 2006; Mohammadi *et al.*, 2008; Pourdad and Mohammadi, 2008; Mohammadi and Pourdad, 2009), and no studies on repeatability and relationships among stability parameters have been conducted on safflower.

Therefore, the objectives of this study were to: (1) study the relationships among parametric and non-parametric stability parameters and their associations with safflower mean seed yield over a wide range of different environments; and (2) study the repeatability of these parameters across consecutive years and environmental sets.

MATERIALS AND METHODS

Experimental materials and sites

The safflower genotypes used in this study were 14 advanced breeding lines selected from the germplasm collection (Pourdad and Singh, 2002) of a safflower breeding program at Iran's Dryland Agricultural Research Institute (DARI). Genotypes were tested during the 2000 to 2005 growing seasons at 10 different locations including Kermanshah, Maragheh, Khoramabad, Zanjan, Ardabil, Kordestan, Shirvan, Ilam, Kohdasht and Gachsaran. As there were data missing for four locations in 2000, the total number of environments was 46 (Table 1). Experiments were planted under rainfed conditions in the autumn (34 environments) and spring (12 environments) growing seasons. Genotypes were evaluated using a randomized complete block design with three replications in each environment. Plot size was 4 × 1.5 m including 5 rows with 30 cm row spacing and 10 cm within-row spacing. Fertilizer application was 50 kg N ha^{-1} and 50 kg P_2O_5 ha^{-1}.

Data for the 46 environments were grouped into five years and three seed yield subsets based on total mean yield of experiments, i.e., low (< 500 kg ha^{-1}), medium (500-1000 kg ha^{-1}) and high (> 1000 kg ha^{-1}).

Analysis of variance

A combined analysis of variance was performed for each year, for three yield subsets and over all environments (locations and years). The phenotypic variance (σ^2_p) was partitioned into genotype genetic variance (σ^2_g) and genotype × environment interaction variance (σ^2_{ge}). Repeatability values $h^2 = \sigma^2_g / \sigma^2_p$ were estimated as measures of the effectiveness of each test environment for differentiating among genotypes (Guillen-Portal *et al.,* 2004). The treatment sum of squares (SS_{TRMT}) was partitioned into its three components: genotype (SS_G), environment (SS_E), and genotype × environment interaction (SS_{GE}). Furthermore, the SS_{GE} was also partitioned into IPCA1, IPCA2 and IPCA3 (Gauch, 1992).

To assess the repeatability of estimates of stability, Spearman's rank correlation coefficients were calculated between years, yield subsets, consecutive years and each year versus the remaining years. All statistical analyses were carried out using SAS version 9 (SAS Institute, 2002).

RESULTS

A combined analysis of variance across test

Table 1. Genotype description and environmental characterization of safflower multi-environment trials

Genotype	Origin	Spine	Flower color	Location	Altitude (m)	Rainfall (mm)	Soil type	Mean temperature °C	
								Min	Max
1-Sina	Iran	Spiny	Yellow-orange	1-Sararood	1351	455	Clay-loam	-15	44
2-Syrian	Syria	Spineless	Red	2-Maragheh	1400	365	Clay-loam	-27	39
3-CW-4440	USA	Spiny	Yellow	3-Gachsaran	710	460	Silt-loam	-2	46
4-Lesaf	Canada	Spiny	Yellow	4-Shirvan	1131	267	Clay-loam	-15	38
5-Cyprus Bregon	Unknown	Spiny	Yellow	5-Kordestan	1850	350	Clay-loam	-23	40
6-CW-74	USA	Spiny	Yellow	6-Zanjan	1875	320	Clay-loam	-15	30
7-Kino-76	Mexico	Spiny	Yellow	7-Ardabil	1350	380	Silt-loam	-25	35
8-S-541	USA	Spiny	Yellow	8-Ilam	975	520	Loam	-5	47
9-PI-250536	Egypt	Spineless	Yellow	9-Khoramabad	1171	520	Silt-loam	-11	26
10-PI-250537	Egypt	Spiny	Yellow	10-Kohdasht	1198	405	Loam	-3	43
11-Hartman	USA	Spiny	Yellow						
12-Gila	USA	Spiny	Yellow						
13-Isfahan local	Iran	Spineless	Red						
14-Dinçer	Turkey	Spiny	Yellow						

environments in each growing season and three yield subsets showed that environment main effect was highly significant (P<0.01) (Table 2). The SS_E average was 83.7% of SS_{TRMT} and ranged from 63.6 to 96%. The genotype main effects (SS_G) were significant in five out of eight years/yield subsets and the average was 2.2% of SS_{TRMT}. The G × E effects (SS_{GE}) were significant and, on average, accounted for 14.1% of the SS_{TRMT}. The SS_G contribution was very low, and its average was seven fold smaller than the SS_{GE}. The AMMI analysis showed that the average of the first, second and third interaction principal component axes explained 43.9%, 21.6% and 13.5% of the G × E sum of squares, respectively. For 2004 growing season AMMI1 model (59.3%), for 2001 and 2002 growing seasons AMMI2 model (75.2% and 73.5%, respectively) and for the remaining growing seasons/yield subsets AMMI3 model fitted the data well. For phenotypic variance (σ^2_p) partitioning, genetic variance (σ^2_g) accounted for 46.5% and 74.3% of σ^2_p in the 2001 growing season and the medium yield subset (Med), respectively. According to Eagles and Frey (1977) and Kumar *et al.* (1998), genetic parameters are repeatable if they show consistent results in different environment subsets. Therefore, estimated σ^2_g was highly repeatable and indicated effective differentiation among genotypes (Guillen-Portal *et al*., 2004). In 2001 and medium yield subset (Med) with the high h^2 and low σ^2_{ge} (22.5% and 10.1%, respectively), genotype evaluation could be safely based on mean performance. In contrast, the remaining years/yield subsets showed low h^2, indicating ineffective genotype differentiation. With high (56.3%) to medium (32.1%) σ^2_{ge} and low h^2, crossover interaction is to be expected.

The rank correlation between mean yields with stability measures showed that mean yield was significantly and positively correlated with P_i over five years and three yield subsets (Table 3). There was a strong positive correlation between mean yield and GAI and a negative one between mean yield and $S_i^{(6)}$ negatively over all years and subsets except 2005. Rank correlations of yield with four non-parametric ($NP_i^{(2)}$, $NP_i^{(3)}$, $NP_i^{(4)}$ and $S_i^{(3)}$) and two parametric (b_i and S^2x_i) stability measures were significant in six of the eight years/subsets. No other stability measures showed highly repeatable associations with yield (Table 3).

Rank correlations between stability measures are shown in Table 4. Due to the high number of stability measures, the correlation matrix was very long. Hence, the only correlations shown are those that were significant over all years/subsets or had only one or two non-significant rank correlations (Table 4).

Results revealed that for nine pairs of stability measures (i.e., b_i with S^2_{xi}, CV_i with I_i, $S_i^{(2)}$ with $NP_i^{(1)}$, $S_i^{(6)}$ with $S_i^{(3)}$ and $NP_i^{(2)}$, $NP_i^{(3)}$ with $S_i^{(3)}$, $S_i^{(6)}$ $NP_i^{(2)}$ and $NP_i^{(4)}$) there was significant rank correlation over all years and yield subsets. For seven pairs of stability measures, only one non-significant rank correlation was observed, and only two were observed for eight pairs of measures. Significant correlations between these stability measures were highly repeatable.

The rank correlations of stability measures obtained in consecutive single years were generally non-significant and average correlations were low (Table 5). Genotype ranking according to these stability measures did not appear repeatable across environments. The rank correlation of stability measures among three yield subsets was generally non-significant, except for S^2_{xi}. The rank correlation of stability measures between each year/subset and the remaining environments were non-significant, except for P_i and $NP_i^{(2)}$ which showed three significant correlations out of five. The four stability measures (i.e., b_i, S^2_{xi}, GAI and $NP_i^{(3)}$) showed

Table 2. Summary of analysis of variance, partitioning of genotype, genotype × environment interaction (GEI) sum of squares and components of phenotypic variance for years and yield potential groups

	2001	2002	2003	2004	2005	Low	Medium	High	
No. of environments	12	8	8	9	9	18	15	13	
					SS_{TRMT}(%)				**Average**
Environments(SS_E)	94.0** (11)	90.7** (7)	79.5** (7)	92.1** (8)	96.0** (8)	63.6** (17)	70.3** (14)	83.4** (12)	83.7
Genotypes (SS_G)	0.9* (13)	1.5** (13)	2.9^{ns} (13)	1.2* (13)	0.6^{ns} (13)	2.5^{ns} (13)	6.5** (13)	1.8* (13)	2.2
GEI (SS_{GE})	5.2** (143)	7.8** (91)	17.6** (91)	6.8** (104)	3.4* (104)	33.8** (221)	23.2** (182)	14.7** (156)	14.1
					SS_{GEI}(%)				
SS_{IPCA1}	48.1** (23)	52.9** (19)	50.6** (19)	59.3** (20)	39.1** (20)	25.6** (29)	32.9** (26)	43.0** (24)	43.9
SS_{IPCA2}	27.1** (21)	20.6** (17)	24.6** (17)	16.2^{ns} (18)	30.3* (18)	16.4** (27)	17.0** (24)	20.9** (22)	21.6
SS_{IPCA3}	12.7^{ns} (19)	11.0^{ns} (15)	10.3* (15)	10.5^{ns} (16)	15.3* (16)	15.3** (25)	13.9* (22)	19.3** (20)	13.5
					σ^2_p(%)				
$H^2= \sigma^2_g/\sigma^2_p$	46.5	23.3	14.1	27.3	24.1	21.4	74.3	33.7	33.1
σ^2_{ge}/σ^2_p	22.5	45.9	56.3	25.4	9.3	32.1	10.1	29.4	28.9

Values in parentheses indicate the degree of freedom (df).
*** and **: Significant at the 0.05 and 0.01 probability levels, respectively.**
ns: Not significant.
$SS_{TRMT} = SS_E + SS_G + SS_{GE}$
IPCA1, IPCA2 and IPCA3 are the first, second and third interaction principal components, respectively.
σ^2_p, σ^2_g, σ^2_{ge} and H^2 are phenotypic, genetic, genotype × environment interaction variances and repeatability value, respectively.

Table 3. Rank correlations between genotypic seed yield and stability measures for different environments within years and yield potential groups

	2001	2002	2003	2004	2005	Low	Mid	High
Yield with P_i	0.92**	0.94**	0.75**	0.93**	0.93**	0.92**	0.93**	0.88**
Yield with GAI	0.83**	0.96**	0.86**	0.90**	ns	0.96**	0.98**	0.92**
Yield with $S_i^{(6)}$	-0.63*	-0.60*	-0.72**	-0.72**	ns	-0.69**	-0.78**	-0.78**
Yield with $NP_i^{(2)}$	-0.79**	-0.55*	ns	-0.78**	ns	-0.69**	-0.88**	-0.94**
Yield with $NP_i^{(3)}$	-0.79**	-0.65*	ns	-0.80**	ns	-0.71**	-0.88**	-0.95**
Yield with $NP_i^{(4)}$	-0.71**	-0.72**	-0.57*	-0.68**	ns	-0.67**	ns	-0.87**
Yield with b_i	-0.69**	ns	-0.62*	-0.82**	-0.85**	ns	-0.57*	-0.67**
Yield with S^2x_i	-0.73**	ns	-0.67*	-0.81**	-0.83**	ns	-0.60*	-0.71**
Yield with $S_i^{(3)}$	-0.58*	ns	-0.55*	-0.60*	ns	-0.53*	-0.67*	-0.60*
Yield with I_i	ns	0.74**	ns	ns	ns	0.66*	0.88**	ns
Yield with CV_i	ns	-0.60*	ns	ns	ns	ns	ns	-0.61*
Yield with S^2d_i	ns	ns	ns	-0.97**	ns	ns	ns	ns
Yield with W^2i	ns	ns	ns	ns	ns	ns	-0.69**	ns
Yield with $NP_i^{(1)}$	ns	ns	ns	ns	ns	ns	ns	-0.62*
Yield with IPCA1	ns	ns	ns	ns	ns	ns	ns	ns
Yield with IPCA2	ns	ns	ns	ns	ns	ns	ns	ns
Yield with IPCA3	ns	ns	ns	ns	ns	ns	ns	ns
Yield with ASV	ns	ns	ns	ns	ns	ns	ns	ns
Yield with $S_i^{(1)}$	ns	ns	ns	ns	ns	ns	ns	ns
Yield with $S_i^{(2)}$	ns	ns	ns	ns	ns	ns	ns	ns

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

repeatability in the correlation between yield subsets and the remaining environments (Table 5).

Hierarchical clustering based on ranks of genotypes by different yield stability measures over 46 environments using the complete linkage method indicated that the 20 stability measures could be divided into six distinct groups (Fig. 1). It has been found that three non-parametric measures of Thennarasu (1995) (i.e., $NP_i^{(2)}$, $NP_i^{(3)}$ and $NP_i^{(4)}$) and two of Huehn (1979) (i.e., $S_i^{(3)}$ and $S_i^{(6)}$) clustered together, indicating that these six statistics were similar in their capacity for classifying genotypes according to yield stability under different environmental conditions. Clusters 1, 2 and 6 were parametric stability measures, whereas cluster 5 was a non-parametric stability measure. IPCA2 and IPCA3 were the only parametric measures that were classified with non-parametric measures. The mean rank correlation within each cluster showed that yield stability statistics in clusters 1, 2, 5 and 6 had a strong correlation (Fig. 1).

DISCUSSION

The highly significant environmental effect and its high proportion in SS_{TRMT} (83.7%) could be attributed to the large differences across locations and seasons, which ranged from cold (Maragheh, Zanjan, Kordestan and Ardabil) to warm (Gachsaran and Kohdasht), with varying amounts of precipitation in each season (Table 1). On the other hand,

Table 4. Rank correlation among stability measures for different environment within years and subsets.

Correlations	2001	2002	2003	2004	2005	2001-05	Low	Medium	High
b_i with S^2_{xi}	0.99**	0.97**	0.87**	0.99**	0.99**	0.99**	0.61*	0.74**	0.99**
b_i with CV_i	0.88**	0.65*	0.63*	0.85**	0.74**	0.86**	ns	ns	0.92**
b_i with P_i	-0.87**	ns	-0.92**	-0.87**	-0.89**	-0.88**	ns	-0.73**	-0.77**
S^2_{di} with W_i^2	0.93**	0.99**	0.95**	ns	0.97**	0.97**	0.99**	ns	0.95**
S^2_{xi} with CV_i	0.86**	0.66*	0.81**	0.85**	0.75**	0.86**	0.86**	ns	0.95**
S^2_{xi} with P_i	-0.90**	ns	-0.79**	-0.87**	-0.87**	-0.86**	ns	-0.64*	-0.76**
CV_i with I_i	-0.93**	-0.96**	-0.88**	-0.75**	-0.94**	-0.90**	-082**	-0.74**	-0.82**
GAI with $S_i^{(6)}$	0.67**	ns	0.64*	0.77**	ns	0.89**	0.57*	0.73**	0.65*
GAI with $NP_i^{(2)}$	0.84**	ns	ns	0.88**	0.64*	0.87**	0.55*	0.82**	0.84**
GAI with $NP_i^{(3)}$	0.78**	0.59*	ns	0.89**	0.70**	0.86**	0.58*	0.83**	0.86**
GAI with P_i	0.68**	0.93**	ns	0.85**	ns	0.75**	0.96**	0.96**	0.82**
$S_i^{(2)}$ with $S_i^{(3)}$	0.74**	ns	0.58*	0.89**	0.90**	ns	0.82**	0.77**	0.84**
$S_i^{(2)}$ with $S_i^{(6)}$	0.54*	0.72**	ns	0.72**	0.79**	ns	0.61*	0.61*	0.64*
$S_i^{(2)}$ with $NP_i^{(1)}$	0.72**	0.68**	0.78**	0.60*	0.84**	0.61*	0.88**	0.67**	0.83**
$S_i^{(3)}$ with $S_i^{(6)}$	0.93**	0.72**	0.88**	0.93**	0.93**	0.97**	0.88**	0.95**	0.93**
$S_i^{(3)}$ with $NP_i^{(1)}$	0.86**	0.68**	ns	0.76**	0.75**	0.79**	0.61*	0.69**	0.90**
$S_i^{(3)}$ with $NP_i^{(2)}$	0.77**	ns	0.74**	0.70**	0.64*	0.86**	0.77**	0.85**	0.68**
$S_i^{(3)}$ with $NP_i^{(3)}$	0.75**	0.57*	0.88**	0.76**	0.53*	0.93**	0.80**	0.89**	0.71**
$S_i^{(6)}$ with $NP_i^{(2)}$	0.88**	0.83**	0.63*	0.85**	0.71**	0.93**	0.86**	0.93**	0.81**
$S_i^{(6)}$ with $NP_i^{(3)}$	0.83**	0.90**	0.70**	0.83**	0.57*	0.97**	0.87**	0.97**	0.84**
$NP_i^{(1)}$ with $NP_i^{(2)}$	0.60*	ns	0.67**	0.67**	0.55*	0.66**	ns	0.70**	0.61*
$NP_i^{(2)}$ with $NP_i^{(3)}$	0.91**	0.87**	0.88**	0.87**	0.85**	0.98**	0.95**	0.96**	0.98**
$NP_i^{(2)}$ with $NP_i^{(4)}$	0.84**	0.74**	0.56*	0.64*	ns	0.91**	0.79**	0.53*	0.85**
$NP_i^{(3)}$ with $NP_i^{(4)}$	0.89**	0.76**	0.69**	0.68**	0.59*	0.91**	0.81**	0.66*	0.84**

*** and **: Significant at the 0.05 and 0.01 probability levels, respectively.**
ns: Not significant.

the low genotypic effect (2.2%) was due to the plant materials, which were advanced genotypes selected in a breeding program. These results are in agreement with data reported for cotton (Baxevanos *et al.*, 2008; Kerby *et al.*, 1996, 2001) and winter wheat (Yan *et al.*, 2000).

Repeatable rank correlations between mean yield with four parametric (P_i, GAI, b_i and S^2x_i) and five non-parametric ($S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(2)}$, $NP_i^{(3)}$ and $NP_i^{(4)}$) stability measures (Table 3) indicated the possibility of using these statistics simultaneously with yield for selecting stable, high yielding genotypes. This logic was used by Kang and Pham (1991) to develop a simultaneous yield and stability selection model. Repeatability of rank correlation between mean yield and b_i was reported in soybean (Sneller *et al.*, 1997), and repeatability of stability estimators for downy mildew incidence was reported in pearl millet (Virk *et al.*, 1985). In this study the superiority index (P_i) showed strong, significant rank correlation with mean yield in all years and yield subsets, and displayed the highest repeatability. A very serious concern in any breeding program is the possibility of rejecting a potentially useful cultivar whose mean may not be high but that shows good adaptability to a relatively narrow niche of environments, or accepting a cultivar whose mean may be high but that shows considerable variation over certain locations. Lin and Binns (1991) recommended the P_i measure to overcome this negative aspect of stability analysis.

Rank correlation coefficients between stability measures revealed that non-parametric statistics were more correlated than parametric statistics over years and yield subsets (Table 4). Due to the high repeatability of correlation pairs, it is possible to use one of these stability measures instead of other measures to select genotypes in a breeding program. In non-parametric stability measures, $S_i^{(3)}$ can be used instead of $S_i^{(2)}$, $S_i^{(6)}$, $NP_i^{(1)}$, $NP_i^{(2)}$ and $NP_i^{(3)}$, and $NP_i^{(2)}$ can be used instead of $NP_i^{(1)}$, $NP_i^{(3)}$, $NP_i^{(4)}$ and $S_i^{(6)}$. Furthermore, $NP_i^{(3)}$ can be used instead of $S_i^{(6)}$ and $NP_i^{(4)}$, and $S_i^{(2)}$ can be used instead of $NP_i^{(1)}$ and $S_i^{(6)}$. Results of the cluster analysis were in agreement with the above rank correlations as five non-parametric statistics grouped in cluster 5 with a strong positive mean correlation (0.71) (Fig. 1). Positive significant correlations between non-parametric statistics were reported by Scapim *et al.* (2000) in maize, Ebadi Segherloo *et al.* (2008) in chickpea, Mohammadi and Amri (2008) in durum wheat and Mohammadi *et al.* (2007) in bread wheat. For parametric stability measures, b_i can be used instead of S^2_{xi}, CV_i and P_i; S^2_{xi} can be used instead of CV_i and P_i. Furthermore, CV_i can be used instead of I_i and S^2_{di} instead of W_i^2. These stability parametric measures were classified in clusters 1 and 2, and had a strong, positive mean correlation (0.74 and 0.70, respectively). A strong, positive correlation between S^2_{xi} and CV_i, and also between W_i^2 and S^2_{di} was reported by Mohebodini *et al.* (2006) in lentil, Mohammadi and Amri (2008) in durum wheat, Fikere *et al.* (2008) in faba bean and Mekbib (2003) in common bean. The highly repeatable correlation between parametric and non-parametric stability measures was observed only between GAI with $S_i^{(6)}$, $NP_i^{(2)}$and $NP_i^{(3)}$; thus, GAI could be used instead of these three non-parametric measures. The strong

Table 5. Rank correlations of stability measures between two consecutive years, yield subsets and each year/subse

	Consecutive single years				Subsets						Year/su
Correlation	**2001-2002**	**2002-2003**	**2003-2004**	**2004-2005**	**Low-Mid**	**Low-High**	**Mid-High**	**2001-Rest**	**2002-Rest**	**2003-Rest**	**2004-Rest**
b_i	0.52	-0.78**	-0.62*	0.02	0.46	0.51	0.61*	0.77**	0.27	-0.43	0.47
S^2_{di}	-0.01	0.29	0.28	-0.16	-0.33	-0.55*	0.50	0.40	0.20	0.33	0.13
S^2_{xi}	0.53*	-0.46	-0.31	0.04	0.90**	0.59*	0.63*	0.73**	0.39	-0.21	0.51
CV_i	0.35	-0.19	-0.08	0.24	0.41	0.41	-0.03	0.37	0.17	-0.16	0.81**
P_i	0.36	0.09	-0.48	0.16	0.43	0.32	0.38	0.65*	0.55*	-0.06	0.34
W^2_i	0.02	0.34	0.37	-0.17	0.19	-0.37	0.06	0.65*	0.04	0.32	0.42
I_i	0.12	0.10	0.24	0.16	0.35	0.14	-0.04	0.04	0.44	-0.02	0.66*
IPCA1	-0.35	-0.09	-0.01	-0.24	0.00	-0.17	-0.25	0.26	-0.17	0.42	0.17
IPCA2	0.01	0.08	0.41	0.54*	0.01	0.24	0.23	0.26	0.11	-0.01	0.42
IPCA3	0.08	0.00	-0.68**	-0.09	-0.09	0.02	0.09	-0.04	0.16	-0.18	-0.30
ASV	0.05	0.20	0.13	-0.17	-0.29	0.02	0.24	0.46	0.21	0.55*	0.43
GAI	0.31	0.64*	0.26	-0.02	0.57*	0.42	0.49	0.46	0.67**	0.59*	0.47
$S_i^{(1)}$	0.48	0.59*	0.13	-0.04	-0.21	0.19	-0.48	0.59*	0.59*	0.53	0.20
$S_i^{(2)}$	0.08	-0.02	0.06	0.04	0.18	-0.26	-0.12	0.55*	0.31	-0.06	0.27
$S_i^{(3)}$	0.08	-0.33	0.13	-0.35	0.02	-0.18	-0.18	0.45	0.34	0.19	0.34
$S_i^{(6)}$	0.16	0.10	0.14	-0.26	0.37	0.11	0.07	0.33	0.61*	0.46	0.44
$NP_i^{(1)}$	0.11	-0.27	0.26	0.12	0.15	-0.11	0.12	0.58*	0.19	-0.01	0.67*
$NP_i^{(2)}$	0.18	-0.02	0.31	-0.26	0.53	0.11	0.33	0.65*	0.43	0.54*	0.58*
$NP_i^{(3)}$	0.24	-0.02	0.18	0.06	0.34	0.38	0.48	0.66*	0.49	0.37	0.56*
$NP_i^{(4)}$	0.44	0.46	0.31	0.24	0.02	0.22	0.44	0.74**	0.47	0.49	0.36

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

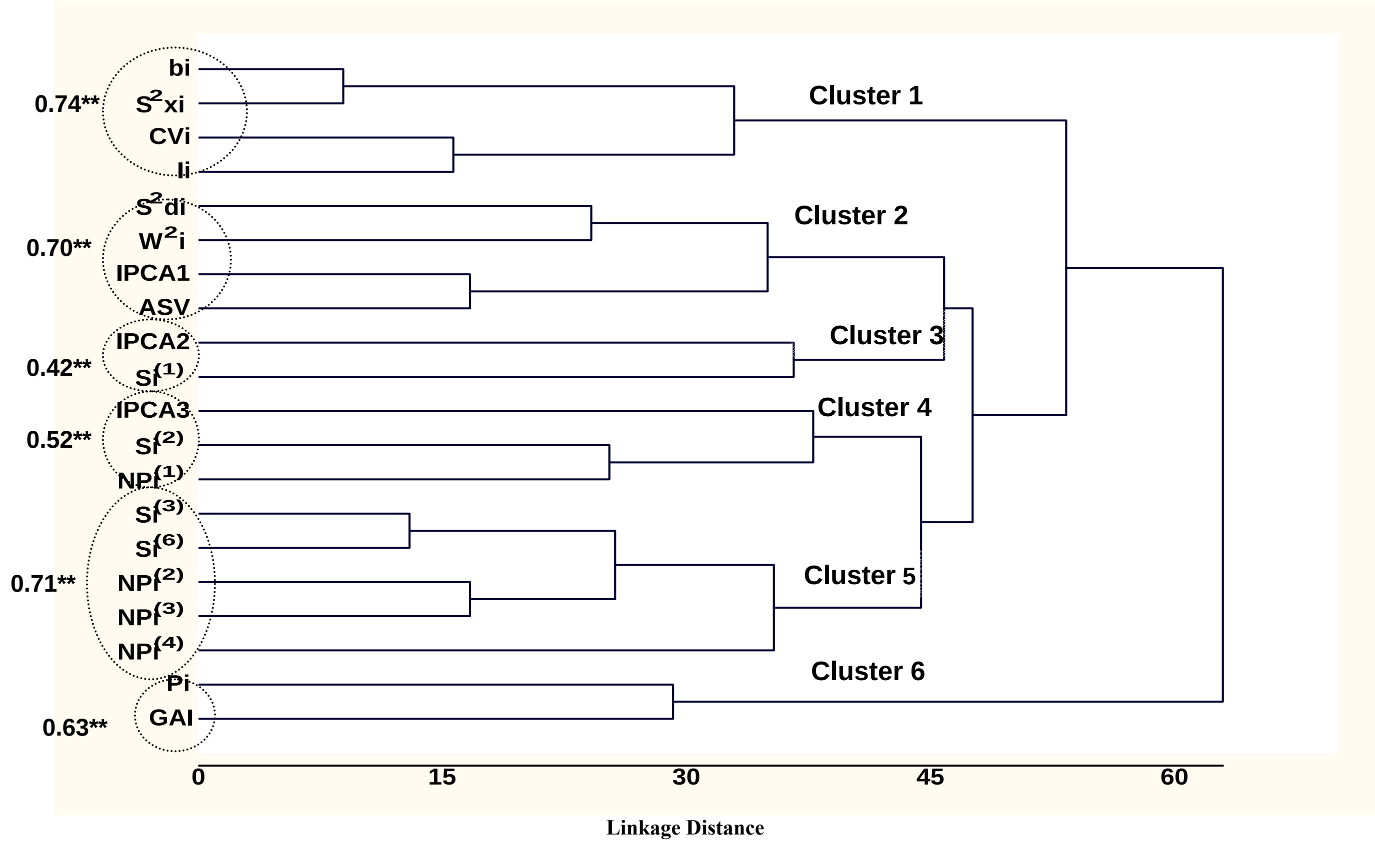

Fig. 1. Dendrogram of hierarchical grouping for 20 yield stability measures and rank correlations

Table 6. Cluster, group, mean of rank correlations and the most stable genotype selected by stability measures within each cluster

Cluster	Group	Mean of rank correlations	Most stable genotype by each stability measure
1	CV_i , I_i , b_i, S^2_{xi}	0.74**	G14, G6, G14, G8
2	S^2_{di} , w^2_i , IPCA1, ASV	0.70**	G7, G4, G2, G4
3	IPCA2, $S_i^{(1)}$	0.42**	G12, G7
4	IPCA3 , $S_i^{(2)}$, $NP_i^{(1)}$	0.52**	G13, G1, G4
5	$S_i^{(3)}$, $S_i^{(6)}$, $NP_i^{(2)}$, $NP_i^{(3)}$, $NP_i^{(4)}$	0.71**	G11, G7, G7, G7, G7
6	P_i , GAI	0.63**	G1, G1

**: Significant at the 0.01 probability level.

negative correlation between GAI and the three above mentioned non-parametric measures was also reported by Mohammadi and Amri (2008) in durum wheat. Identification of the most stable genotype by different stability measures (Table 6) revealed that non-parametric statistics were more similar in their capacity to group genotypes according to yield stability than parametric statistics. Therefore, $S_i^{(6)}$, $NP_i^{(2)}$, $NP_i^{(3)}$, $NP_i^{(4)}$ and $S_i^{(1)}$ identified G7 as the most stable genotype over all 46 environments. According to results of rank correlation, clustering and identification of stable genotypes, it can be concluded that one of the above non-parametric stability measures can be used instead of the other four non-parametric measures in the safflower breeding program.

In this study, repeatability of stability measures in consecutive single years was low, indicating that these statistics apparently have little use in cultivar selection. The low repeatability of b_i , S^2_{di} and IPCA was also reported by Ortiz *et al.* (2001) in bread wheat, Sneller *et al.* (1997) in soybean and Kumar *et al.* (1998) in chickpea. The repeatability of GAI, Pi, I_i and non-parametric stability statistics has not been previously published. The repeatability of yield stability measures in subsets was generally low, but it was moderate for b_i and GAI and highly repeatable for S^2_{xi} . Sneller *et al.* (1997) estimated moderate repeatability for b_i derived from two-year data. Eagles and Frey (1977), Jalaluddin and Harrison (1993), and Leon and Becker (1988) also reported similar results. Estimated correlations between each year/subset and the remaining environments were more significant for stability statistics than consecutive single years and subsets. There was high repeatability for P_i, GAI, $NP_i^{(3)}$ and $NP_i^{(2)}$, and moderate repeatability for b_i, S^2_{xi}, $NP_i^{(4)}$ and $S_i^{(6)}$.

The results of this study revealed that

repeatability of the stability measures was generally low to moderate despite highly significant environmental and G × E interaction effects and a high number of environments (46 environments). Therefore, it is speculated that increasing the number of testing environments does not necessarily lead to greater repeatability of stability statistics.

In conclusion, two parametric stability measures, the superiority measure (P_i) and the geometric adaptability index (GAI), as well as two of Thennarasu's non-parametric stability measures ($NP_i^{(2)}$ and $NP_i^{(3)}$), had strong rank correlations with seed yield and high repeatability. Therefore, these statistics could be used simultaneously with seed yield to select genotypes with high yield and high yield stability in safflower breeding programs.

ACKNOWLEDGMENT

The data used in this study were provided by the National Safflower Research Program of Iran's Dryland Agricultural Research Institute (DARI). The author would like to thank the safflower breeding program group at the agricultural research stations in Sararood, Maragheh, Gachsaran, Shirvan, Kordestan, Ilam, Zanjan, Ardabil, Khoramabad and Kohdasht for their assistance.

REFERENCES

Annicchiarico, P. 1997. Joint regression vs. AMMI analysis of genotypes environment interactions for cereals in Italy. Euphytica 94: 53-62.

Arshad, M., A. Bakhsh, A. M. Haqqani, and M. Bashir. 2003. Genotype-environment interaction for grain yield in chickpea (*Cicer arietinum* L.). Pak. J. Bot. 35(2): 181-186.

Baxevanos, D., C. Goulas, S. Tzortzios, and A. Mavromatis. 2008. Interrelationship among and repeatability of seven stability indices estimated from commercial cotton (*Gossypium hirstum* L.) variety evaluation trials in three Mediterranean countries. Euphytica 161: 371-382.

Becker, H. C. 1981. Biometrical and empirical relations between different concepts of phenotypic stability. Pp. 307-314. *In* Gallais, A. (ed.). Quantitative genetics and breeding methods. I. N. R. A., Versailles, France.

Becker, H. C., and J. Léon. 1988. Stability analysis in plant breeding. Plant Breed. 101: 1-23.

Crossa, J. 1990. Statistical analysis of multilocation trials. Adv. Agron. 44: 55-85.

Eagles, H. A., and K. J. Frey. 1977. Repeatability of the stability variance parameters in oats. Crop Sci. 17: 253-256.

Ebadi Segherloo, A., S. H. Sabaghpour, H. Dehghani, and M. Kamrani. 2008. Non-parametric measures of phenotypic stability in chickpea genotypes (*Cicer arietinum* L.). Euphytica 162: 221-229.

Eberhart, S. A., and W. A. Russell. 1966. Stability parameters for comparing varieties. Crop Sci. 6: 36-40.

Elfadl, E. Y., C. Reinbrecht, C. Frick, S. Von Witzke, S. Rudolphi, and W. Claupein. 2005. Potentioa des Anbaus Von Saflor (*Carthamus tinctorius* L.) Unter den Bedengungen des Okologischen Landbaos in Mitteleuropa. Pp. 39-43. *In* Proceedings of the 6th International Safflower Conference, Istanbul Turkey.

Eskridge, K. M. 1990. Selection of stable cultivars using a safety-first rule. Crop Sci. 30: 369-374.

Fikere, M., T. Tadesse, and T. Letta. 2008. Genotype-environment interactions and stability parameters for grain yield of faba bean (*Vicia faba* L.) genotypes grown in southeastern Ethiopia. Int. J. Sustain. Crop Prod. 3(6): 80-87.

Francis, T. R., and L. W. Kannenberg. 1978. Yield stability studies in short-season maize. I. A descriptive method for grouping genotypes. Can. J. Plant Sci. 58: 1029-1034.

Gauch, H. G. 1992. Statistical Analysis of Regional Yield Trials: AMMI Analysis of Factorial Designs. Elsevier, New York. pp. 278.

Guillen-Portal, F. R., W. K. Russell, K. M. Eskridge, D. D. Baltensperger, L. A. Nelson, N. E. D'Croz-Mason, and B. E. Johnson. 2004. Selection environments for maize in the U.S. Western High Plains. Crop Sci. 44: 1519-1526.

Huehn, M. 1979. Beitrage zur erfassung der phanotypischen stabilitat. EDV in Medizin und Biologie 10: 112-117.

Huehn, M. 1996. Non-parametric analysis of genotype × environment interactions by ranks. Pp. 213-228. *In* Kang, M. S., and H. G. Gauch (eds.). Genotype by environment interaction. CRC Press, Boca Raton, FL.

Jalaluddin, M. D., and S. A. Harrison. 1993. Repeatability of stability statistics for grain yield in wheat. Crop Sci. 33: 720-725.

Kang, M. S, and H. N. Pham. 1991. Simultaneous selection for high yielding and stable crop genotypes. Agron. J. 83: 161-165.

Kataoka, S. 1963. A stochastic programming model. Econometrika 31: 181-196.

Kerby, T., L. Lewinsky, J. Burgess, M. Bates, and J. Presley. 1996. Genetic and environmental contributions to earliness. Pp. 592-594. *In* Proceedings Beltwide Cotton Conference, National Cotton Council.

Kerby, T., J. Burgess, K. Lege, and D. Albers. 2001. Partitioning variety environment contribution to variation in yield, plant growth and fiber quality. Pp. 528-532. *In* Proceedings of Beltwide Cotton Conferenec, National Cotton Council.

Kumar, S., O. Singh, H. A. Vanrheenen, and K. V. S. Rao. 1998. Repeatability of different stability parameters for grain yield in chickpea. Plant Breed. 117: 143-146.

Leon, J., and H. C. Becker. 1988. Repeatability of some statistical measures of phenotypic stability–correlation between single year results and multi-year results. Plant Breed. 100: 137-142.

Lin, C. S., and M. R. Binns. 1988. A superiority measure of cultivar performance for cultivar × location data. Can. J. Plant Sci. 68: 193-198.

Lin, C. S., M. R. Binns, and L. P. Lefkovitch. 1986. Stability analysis: Where do we stand? Crop Sci. 26: 894-900.

Lin, C. S., and M. R. Binns. 1991. Assessment of a method for cultivar selection based on regional trial data. Theor. Appl. Genet. 82: 379-388.

Mahasi, M. J., R. S. Pathak, F. N. Wachira, T. C. Riungu, M. G. Kinyua, and J. K. Waweru. 2006. Genotype by environment (GE) interaction and stability in safflower (*Carthamus tinctorius* L.). Asian J. of Plant Sci. 5(6): 1017-1021.

Mekbib, F. 2003. Yield stability in common bean (*Phaseolus vulgaris* L.) genotypes. Euphytica 130: 147-153.

Mohamadi, R. and A. Amri. 2008. Comparison of parametric and non-parametric methods for selecting stable and adapted durum wheat genotypes in variable environments. Euphytica 159:419-432.

Mohamadi, R., S. S. Pourdad, and A. Amri. 2008. Grain yield stability of spring safflower (*Carthamus tinctorius* L.). Aust. J. of Agric. Res. 59: 546-553.

Mohammadi, R., and S. S. Pourdad. 2009. Estimation, interrelationships and repeatability of genetic variability parameters in spring safflower using multi-environment trial data. Euphytica 165: 313-329.

Mohammadi, R., A. Abdullahi, R. Haghparast, M. Aghaee, and M. Roustaii. 2007. Non-parametric methods for evaluating winter wheat genotypes in multi-environmental trials. World J. of Agri. Sci. 3(2): 137-242.

Mohebodini, M., H. Dehghani, and S. H. Sabaghpour. 2006. Stability of performance in lentil (*Lens culinaris* Medik) genotypes in Iran. Euphytica 149: 343-352.

Narkhede, B. N., A. B. Deokar, and J. V. Patil. 1984. Phenotypic stability for seed yield in safflower. J. of Maharashtra Agric. Univ. 9(2): 179-181.

Nassar, R., and M. Huehn. 1987. Studies on estimation of phenotypic stability. Biometrics 43: 45-53.

Ortiz, R., W. W. Wagoire, J. Hill, and S. Chandra. 2001. Heritability of and correlation among genotype-by-environment stability statistics for grain yield in bread wheat. Theor. Appl. Genet. 103: 469-474.

Piepho, H.P. 1996. Analysis of genotype environment interaction and phenotypic stability. Pp. 151-174. *In* Kang, M. S. and H. G. Zobel (eds.). Genotype by environment interaction. CRC Press, Boca Raton, FL.

Pourdad, S. S., and A. Beg. 2003. Safflower (*Carthamus tinctorius* L.): An oilseed crop suitable for dryland areas of Iran. Pp. 296-299. *In* Proceedings of the 7th International Conference on Dryland Development. Tehran, Iran (in Persian).

Pourdad, S. S., and R. Mohammadi. 2008. Use of stability parameters for comparing safflower genotypes in multi-environment trials. Asian J. Plant Sci. 7(1): 100-104.

Pourdad, S. S., and J. B. Singh. 2002. Evaluation of germplasm collection of safflower (*Carthamus tinctorius* and *C. oxyacanta*) in dryland conditions of Iran. Indian J. of Genet. and Plant Breeding 62(1): 87-88.

Purchase, J. L., H. Hatting, and C. S. Van Deventer. 2000. Genotype × Environment interaction of winter wheat in South Africa: II. Stability analysis of yield performance. S. Africa Plant Soil 17(3):101-107.

Rangarao, V., and M. Ramachandra. 1979. Stability parameters for yield and its components in safflower. Mysore J. of Agri. Sci. 13: 297-308.

SAS Institute. 2002. SAS/STAT User's Guide, Second Edition. SAS Institute Inc. Cary, NC.

Scapim, C. A., V. R. Oliveira, A. L. Braccinil, C. D. Cruz, C. A. B. Andrade, and M. C. G. Vidigal. 2000. Yield stability in maize (*Zea mays* L.) and correlation among the parameters of the Eberhart & Russell, Lin & Binns and Huehn models. Genet. Mol. Bio. 23: 387-393.

Shukla, G. K. 1972. Some statistical aspects of partitioning genotype-environmental components of variability. Heredity 29: 237-245.

Sneller, C. H., L. Kilgore-Norquest, and D. Dombek. 1997. Repeatability of yield stability statistics in soybean. Crop Sci. 37: 383-390.

Thennarasu, K. 1995. On certain non-parametric procedures for studying genotype-environment interactions and yield stability. Ph. D. Thesis, P. J. School IARI, New Dehli.

Truberg, B., and H. Huehn. 2000. Contribution to the analysis of genotype by environment interactions: Comparison of different parametric and non-parametric tests for interactions with emphasis on crossover interactions. Agron. and Crop Sci. 185: 267-274.

Virk, D. S., S. S. Chahal, and H. S. Pooni. 1985. Repeatability of stability estimators for downy mildew incidence in pearl millet. Theor. Appl. Genet. 70: 102-106.

Wricke, G. 1962. Über eine Methode Zur Erfassung der ökologischen Streubreite in Feldversuchen. Z Pflanzenzuecht 47: 92-96.

Yau, S. K. 2005. Yield increase of barley following safflower in a cool semi-arid Mediterranean area. Pp. 92-97. *In* Proceedings of the 6th International Safflower Conference, Istanbul, Turkey.

Yau, S. K., and L. A. Hunt. 1998. Genotype by environment interaction and crop yields. Plant Breeding Review 16: 135-178.

Yan, W., L. A. Hunt, Q. Sheng and Z. Szlavnics. 2000. Cultivar evaluation and mega-environment investigation based on GGE biplot. Crop Sci. 40:597-605.

Zobel, B. J., and J. Talbert. 1984. Applied forest tree improvement. Wiley, New York. 505 pp.