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

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ABSTRACT


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 (Pi), geometric adaptability index (GAI), regression coefficient (bi) and environmental variance (S2i), 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 (NPi(1), NPi(2) and NPi(3)). 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, NPi(1), NPi(2) and NPi(3). Repeatability of the stability measures obtained in consecutive single years was lower but moderate for bi and GAI in subsets, and highly repeatable for Pi, GAI, NPi(3) and NPi(2) in year/subsets versus the remaining environments. Superiority measure (Pi) and geometric adaptability index (GAI), along with two Thennarasu non-parametric stability measures (NPi(2) and NPi(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 ecovariance (W^2_{ij}), can be used as a measure of its stability (Wricke, 1962). The highest stability is when W^2_{ij} = 0. Shukla’s (1972) stability variance and W^2_{ij} give the same results when ranking genotypes (Becker and Leon, 1988). Francis and Kannenberg (1978) measured stability by combining a coefficient of variation (CV_i) and mean yield. Genotypes with low CV_i 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.

\[
P_i = \frac{\sum_{j=1}^{m} (X_{ij} - M_j)^2}{2E}
\]

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: \(I_i = m_i - Z_{P_i} S_i\) where \(m_i\) = mean yield, \(S_i\) = square root of the environmental variance, and \(Z_{P_i}\) = percentile from the standard normal distribution for which the cumulative distribution function reaches the value P. \(Z_{P_i}\) 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 \(GAI = \frac{P_i}{\left(\overline{X}_1, \overline{X}_2, \ldots, \overline{X}_n\right)}\)

where \(\overline{X}_1, \overline{X}_2, \ldots, \overline{X}_n\) are the means of the first, second and ith 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:

\[
ASV = \left[\frac{SS_{IPCA}}{SS_{IPCA}}\right]^{1/2} + (IPCAX_{score})^{2}
\]

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 (\(S_{i}^{(1)}, S_{i}^{(2)}, S_{i}^{(3)}, S_{i}^{(4)}\)) which are based on yield rank of genotypes in each environment as below:

\[
S_{i}^{(1)} = 2\sum_{j=1}^{m} \sum_{(j \neq i)} (y_j - r_j) \left[\frac{1}{m(m-1)}\right]
\]

\[
S_{i}^{(2)} = \frac{\sum_{j=1}^{m} (y_j - r_i)^2}{m-1}
\]

\[
S_{i}^{(3)} = \frac{\sum_{j=1}^{m} (y_j - r_i)^2}{r_i}
\]
Pourdad: Repeatability and relationship  …

\[ S^{(i)} = \frac{\sum_{j=1}^{m} |r_{ij}^* - \bar{r}_i|}{\bar{r}_i} \]

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 \( \bar{r}_i = \frac{\sum r_{ij}}{m} \).

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

\[ NP^{(1)} = \frac{1}{m} \sum_{i=1}^{m} |r_{ij}^* - M_{ij}^*| \]
\[ NP^{(2)} = \frac{1}{m} \sum_{i=1}^{m} \frac{|r_{ij}^* - M_{ij}^*|}{M_{ij}^*} \]
\[ NP^{(3)} = \frac{2}{m(m-1)} \sum_{j=1}^{m} \sum_{i=j+1}^{m} |r_{ij}^* - r_{ij}^*| / \bar{r}_i \]

where \( r_{ij}^* \) is the rank of adjusted values (\( X_{ij}^* \)), \( M_{ij}^* \) and \( \bar{r}_i \) are the median and mean ranks based on adjusted values, respectively, while \( M_{ij}^* \) and \( \bar{r}_i \) 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\(_2\)O\(_5\) 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 (\( \sigma^2_p \)) was partitioned into genotype genetic variance (\( \sigma^2_g \)) and genotype × environment interaction variance (\( \sigma^2_{ge} \)). 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...
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 (σ²_p) partitioning, genetic variance (σ²_ge) accounted for 46.5% and 74.3% of σ²_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 σ²_ge was highly repeatable and indicated effective differentiation among genotypes (Guillen-Portal et al., 2004). In 2001 and medium yield subset (Med) with the high h² and low σ²_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 h², indicating ineffective genotype differentiation. With high (56.3%) to medium (32.1%) σ²_ge and low h², 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 \( S_i \) 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 Si(3)) and two parametric (b_i and S²xi) 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 S²xi, CV_i with I_i, S_i with NP_i(2), S_i with S_i with NP_i(2), NP_i(3), NP_i(4) and Si(3)) and two parametric (b_i and S²xi) stability measures were significant 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 \( S_i \). The rank correlation of stability measures between each year/substrset 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, S²xi, GAI and NP_i(3)) showed

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

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Origin</th>
<th>Spine</th>
<th>Flower color</th>
<th>Location</th>
<th>Altitude (m)</th>
<th>Rainfall (mm)</th>
<th>Soil type</th>
<th>Mean temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Sina</td>
<td>Iran</td>
<td>Spine</td>
<td>Yellow-orange</td>
<td>1-Sararood</td>
<td>1351</td>
<td>455</td>
<td>Clay-loam</td>
<td>-15 44</td>
</tr>
<tr>
<td>2-Syrian</td>
<td>Syria</td>
<td>Spineless</td>
<td>Red</td>
<td>2-Maragheh</td>
<td>1400</td>
<td>365</td>
<td>Clay-loam</td>
<td>-27 39</td>
</tr>
<tr>
<td>3-CW-4440</td>
<td>USA</td>
<td>Spine</td>
<td>Yellow</td>
<td>3-Gachsaran</td>
<td>710</td>
<td>460</td>
<td>Silt-loam</td>
<td>-7 46</td>
</tr>
<tr>
<td>4-Resaf</td>
<td>Canada</td>
<td>Spine</td>
<td>Yellow</td>
<td>4-Shirvan</td>
<td>1113</td>
<td>267</td>
<td>Clay-loam</td>
<td>-15 38</td>
</tr>
<tr>
<td>5-Cyprus Bregen</td>
<td>Unknown</td>
<td>Spine</td>
<td>Yellow</td>
<td>5-Kordestan</td>
<td>1850</td>
<td>350</td>
<td>Clay-loam</td>
<td>-23 40</td>
</tr>
<tr>
<td>6-CW-74</td>
<td>USA</td>
<td>Spine</td>
<td>Yellow</td>
<td>6-Zanjani</td>
<td>1875</td>
<td>320</td>
<td>Clay-loam</td>
<td>-15 30</td>
</tr>
<tr>
<td>7-Kino-76</td>
<td>Mexico</td>
<td>Spine</td>
<td>Yellow</td>
<td>7-Ardabil</td>
<td>1350</td>
<td>380</td>
<td>Silt-loam</td>
<td>-25 35</td>
</tr>
<tr>
<td>8-S-541</td>
<td>USA</td>
<td>Spine</td>
<td>Yellow</td>
<td>8-Imam</td>
<td>975</td>
<td>520</td>
<td>Loam</td>
<td>-5 47</td>
</tr>
<tr>
<td>9-PI-250536</td>
<td>Egypt</td>
<td>Spineless</td>
<td>Yellow</td>
<td>9-Khoramabad</td>
<td>1171</td>
<td>520</td>
<td>Silt-loam</td>
<td>-11 26</td>
</tr>
<tr>
<td>10-PI-250537</td>
<td>Egypt</td>
<td>Spine</td>
<td>Yellow</td>
<td>10-Kohdasht</td>
<td>1198</td>
<td>405</td>
<td>Loam</td>
<td>-3 43</td>
</tr>
<tr>
<td>11-Hartman</td>
<td>USA</td>
<td>Spine</td>
<td>Yellow</td>
<td>11-Hartman</td>
<td>1198</td>
<td>405</td>
<td>Loam</td>
<td>-3 43</td>
</tr>
<tr>
<td>12-Gila</td>
<td>USA</td>
<td>Spine</td>
<td>Yellow</td>
<td>12-Gila</td>
<td>1198</td>
<td>405</td>
<td>Loam</td>
<td>-3 43</td>
</tr>
<tr>
<td>13-Isfahan local</td>
<td>Iran</td>
<td>Spineless</td>
<td>Red</td>
<td>13-Isfahan</td>
<td>1198</td>
<td>405</td>
<td>Loam</td>
<td>-3 43</td>
</tr>
<tr>
<td>14-Dincar</td>
<td>Turkey</td>
<td>Spine</td>
<td>Yellow</td>
<td>14-Dincar</td>
<td>1198</td>
<td>405</td>
<td>Loam</td>
<td>-3 43</td>
</tr>
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</table>
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., $NP_1$, $NP_2$ and $NP_3$) and two of Huehn (1979) (i.e., $S_{10}$ and $S_{15}$) 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 IPCA1, IPCA2 and IPCA3 are the first, second and third interaction principal components, respectively.

**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,

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 (Pi, GAI, bi and Si(x)) and five non-parametric (Si(6), Si(3), Pi(6), Pi(2) and Pi(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 b1 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 (Pi) 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 Pi measure to overcome this negative aspect of stability analysis.

Rank correlation coefficients between stability measures revealed that non-parametric measures 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, Si(3) can be used instead of Si, Si(6), NPi(1), NPi(2) and NPi(3), and NPi(6) can be used instead of NPi(1), NPi(3), NPi(4) and S(6). Furthermore, NPi(3) can be used instead of S(6) and NPi(6), and S(2) can be used instead of NPi(1) and S(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 chick pea, Mohammadi and Amri (2008) in durum wheat and Mohammadi et al. (2007) in bread wheat. For parametric stability measures, bi can be used instead of Si(x), CVi and Pi; Si can be used instead of CVi and Pi; Furthermore, CVi can be used instead of Ii and S2 instead of Wi. 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 Si(x) and CVi, as well as between Wi and Si 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 Si(6), NPi(2) and NPi(4); 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/subset with remaining years.

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>( b )</td>
<td>0.52</td>
<td>0.01</td>
<td>0.36</td>
<td>0.02</td>
<td>0.46</td>
<td>0.51</td>
<td>0.61*</td>
<td>0.77**</td>
<td>0.27</td>
<td>-0.43</td>
<td>0.47</td>
</tr>
<tr>
<td>( S_{al}^2 )</td>
<td>-0.46</td>
<td>-0.19</td>
<td>0.09</td>
<td>0.16</td>
<td>0.43</td>
<td>0.32</td>
<td>0.38</td>
<td>0.65*</td>
<td>0.55*</td>
<td>-0.06</td>
<td>0.34</td>
</tr>
<tr>
<td>( S_{ai}^2 )</td>
<td>0.53*</td>
<td>-0.31</td>
<td>0.04</td>
<td>0.90**</td>
<td>0.50*</td>
<td>0.63*</td>
<td>0.73**</td>
<td>0.39</td>
<td>-0.21</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>( CV_i )</td>
<td>0.35</td>
<td>-0.08</td>
<td>0.24</td>
<td>0.41</td>
<td>0.41</td>
<td>-0.03</td>
<td>0.37</td>
<td>0.17</td>
<td>-0.16</td>
<td>0.81**</td>
<td></td>
</tr>
<tr>
<td>( P_i )</td>
<td>0.36</td>
<td>-0.48</td>
<td>0.16</td>
<td>0.43</td>
<td>0.32</td>
<td>0.38</td>
<td>0.65*</td>
<td>0.55*</td>
<td>-0.06</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>( W_i )</td>
<td>0.02</td>
<td>0.37</td>
<td>-0.17</td>
<td>0.19</td>
<td>-0.37</td>
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<td>0.14</td>
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<td>0.74**</td>
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* and **: Significant at the 0.05 and 0.01 probability levels, respectively.
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_(6) , NPi_(2) , NPi_(3) , NPi_(4) and S_(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_n, GAI, NPi_(3) and NPi_(2), and moderate repeatability for b_i, S^2_{xi}, NPi_(4) and S_(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) and the geometric adaptability index (GAI), as well as two of Thennarasu’s non-parametric stability measures (NP, (2) and NP, (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.

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REFERENCES