Evaluation of maize hybrids stability using parametric and non-parametric methods

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Abstract
The purpose of the study was to compare four parametric and three nonparametric methods for the assessment of agronomic stability of eight maize cultivars chosen from postregistration trials carried out at 16 locations in Poland for a period of three years. Significant correlations were found between mean yield and two parametric measures: b1 and D1. Of nonparametric statistics only the new proposed measure (R1) was significantly associated with yield (r=0.86), whereas Kang’s rank sum just missed significance (r=0.68). Correlations between parametric and non-parametric measures were in general not significant. Full correlation was found between Wricke’s ecovalence and Shukla’s stability variance. Hühn’s stability measures S1 and S1i were also highly positively associated (r=0.92). As expected high correlation was observed between ecovalence and S1i (r=0.98). The results showed that high yielding cultivars can also be stable. The new proposed method based on homogeneous groups ranks can be a useful alternative to Kang’s rank sum parameter in studies of agronomic stability of maize hybrids.

Keywords: agronomic stability, cultivars, genotype-environment (GxE) interaction, maize

Introduction
In Poland, as many as 147 maize cultivars were on the National Variety List in 2013 (COBORU, 2013). Farmers are interested in those cultivars which will give high and stable yields. And thus, there is a need to investigate the genotype-environment (GxE) interaction which can be useful in microregionalization (targeting cultivars to specific environments). The effects of cultivars and the environments are statistically non-additive, which means that differences in cultivar yields will depend on the environment (Hühn 1996; Yue et al., 1997). It can be concluded from this that the choice of cultivars based on the mean yield in a given environment will be less efficient (Hopkins et al., 1995). To identify stable and superior crop cultivars univariate parametric methods of Finlay and Wilkinson (1963), Eberhart and Russel (1966) have often been used. Eberhart and Russel (1966) proposed regression coefficient to evaluate cultivar responsiveness to environment and deviation mean square (SVar) to assess its yield stability. Shukla (1972) proposed an unbiased estimate of variance (σ2) for the assessment of stability. Significance of the variance points out to the cultivar’s unstable yielding performance. Similar approach was developed by Calirski (1960). Wricke (1962) developed a method of ecovalence, which measures the contribution of each genotype to the sum of squares for the GxE interaction. A low value of this statistic indicates high stability of the variety.

Hanson (1970) introduced a method for evaluation of the genotype stability for a small number of varieties and environments by estimating parameter D. In this procedure, the stability of a variety is defined as deviation of the expected (E) from the stable (S) yield. If certain assumptions like normality, homogeneity of variance, additivity or linearity of genotype and environmental effects are not satisfied, then parametric models can lead to erroneous conclusions. Therefore, some researches proposed non-parametric models which are distribution free and do not require such assumptions (Hühn 1990a; 1990b; Kang 1988; Fox et al., 1990).

Many non-parametric and statistical methods have been developed for testing of GxE interaction (Azalini and Kox 1984; Brederkamp 1974; De Kroon and von der Laan 1981; Hildebrand 1980; Kubinger 1986). One of the advantages of non-parametric measures is that they are easy to calculate and interpret. Kang’s method (1988), also termed rank sum (RS), combines ranked yield and Shukla’s stability variance into one measure, whereas in the method of Fox et al. (1990) ranked cultivars are assigned to three different fractions: top, medium, and bottom. The genotypes in the top third are considered the most desirable because they are high yielding and stable. The methods of Kang and Fox share a common deficiency as they do not take into account the significant differences in yields among the cultivars, and the calculated measures are often poorly correlated with the yield (Mohammadi et al., 2007a; 2007b; 2008. Bujak et al., 2008a; 2008b; 2013) proposed a non-parametric...
method based on distinct homogenous groups ranks ($R_i$) and coefficient of variation (CV) to assess agronomic stability of cultivars. Commonly used multiple comparison tests do not separate means into non-overlapping groups, therefore in the proposed method Haufe and Geidel test (1984) was applied.

The aim of the study is to compare and evaluate the usefulness of parametric and nonparametric methods for estimating agronomic stability of maize hybrids.

**Materials and Methods**

**Experimental material**

A subset of 8 maize hybrids were chosen from postregistration experiments arranged in incomplete block design with four replications at 16 locations for a period of three years. The cultivars Amadeo, Coxximo, ES Paroli, Monumental, System, Asteri, Mas 25A and Silas were chosen because they were common to all years and locations distributed over a wide range of environments in Poland. Harvested plot size was 16m2. Stability analyses were made using the following parametric and non-parametric methods.

**Statistical analysis**

**Parametric methods**

1. **Eberhart and Russell method (1966)**

   Eberhart and Russell (1966) proposed evaluation of the reaction of cultivars to changeable environmental conditions through the use of the linear regression coefficient $b_i$ and variance of deviations from regression $S_{di}^2$:

   $$ b_i = 1 + \frac{\sum(x_i - \bar{x}_i - \bar{\bar{x}} + \bar{\bar{\bar{x}}}) (x_j - \bar{\bar{x}})}{\sum(x_j - \bar{\bar{x}})^2} $$

   where: $x_i$ = yield of the $i^{th}$ cultivar; $x_j$ = mean yield of the $j^{th}$ cultivar; $\bar{x} = \frac{1}{t} \sum x_i$ = overall mean; $E$ = number of environments.

   Varieties having regression coefficient $b_i > 1$ are better adapted to favourable environmental conditions. In the case when $b_i < 1$, they perform better in low yielding environments. If $b_i = 1$, then the varieties are characterized by average adaptability to different environments. Cultivars with variance $S_{di}^2 = 0$ are the most stable, whereas a high value of $S_{di}^2$ indicates low stability.

2. **Shukla's stability variance (1972)**

   The stability statistic of Shukla (1972) is a measure of the share of each particular variety in the GxE interaction.

   $$ \sigma_i^2 = \frac{1}{(t-1)(t-2)} \left[ t(t-1) \sum (x_i - x_j + x) \right] $$

   where: $s$ = number of environments; $t$ = number of varieties.

   A low value of $\sigma_i^2$ testifies to high yield stability of a given cultivar.

3. **Wricke's ecovalence $W_i$ (1962)**

   The ecovalence defines the share of each genotype in the sum of squares of the GxE interaction. A low value of $W_i$ points out to high yield stability of the variety.

   $$ W_i = \sum (x_i - x_j + x) \left( x_i - x_j + x \right)^2 $$

4. **Hanson's genotype stability measure $D_i$ (1970)**

   This method is employed when a number of both cultivars and environments is small. The $D_i$ value is a measure of the share of a given genotype in the variance of the GxE interaction and of the genotype’s reaction to changeable environmental conditions with the use of the Eberhart and Russell regression coefficient $b_i$. It is thus a measure of a cultivar’s stability expressed as deviation of its expected yield ($E_i$) from its stable yield ($S_i$).

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**Table 1** - Assessment of yield stability for the maize cultivars as measured by parametric methods.

<table>
<thead>
<tr>
<th>Cultivars</th>
<th>Yield $t$ ha$^{-1}$</th>
<th>Eberhart and Russell $b_i$</th>
<th>$S_{di}^2$</th>
<th>Hanson $D_i$</th>
<th>Wricke $W_i$</th>
<th>Shukla $\sigma_i^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aster</td>
<td>10.54</td>
<td>1.09</td>
<td>144.25</td>
<td>90.16</td>
<td>941.53</td>
<td>41.84</td>
</tr>
<tr>
<td>ES Paroli</td>
<td>10.48</td>
<td>1.12</td>
<td>288.35</td>
<td>88.99</td>
<td>855.23</td>
<td>37.42</td>
</tr>
<tr>
<td>Coxximo</td>
<td>10.44</td>
<td>0.96</td>
<td>143.23</td>
<td>80.86</td>
<td>796.80</td>
<td>32.12</td>
</tr>
<tr>
<td>MAS 25A</td>
<td>10.42</td>
<td>1.01</td>
<td>242.70</td>
<td>101.78</td>
<td>1643.38</td>
<td>77.83</td>
</tr>
<tr>
<td>Amadeo</td>
<td>10.40</td>
<td>1.01</td>
<td>547.66</td>
<td>95.17</td>
<td>433.98</td>
<td>15.81</td>
</tr>
<tr>
<td>Monumental</td>
<td>10.30</td>
<td>1.03</td>
<td>216.09</td>
<td>94.68</td>
<td>656.00</td>
<td>27.20</td>
</tr>
<tr>
<td>Silas</td>
<td>10.29</td>
<td>0.91</td>
<td>362.80</td>
<td>107.14</td>
<td>1151.75</td>
<td>52.62</td>
</tr>
<tr>
<td>System</td>
<td>9.57</td>
<td>0.86</td>
<td>246.58</td>
<td>110.42</td>
<td>909.93</td>
<td>40.22</td>
</tr>
</tbody>
</table>

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**Table 2** - Estimates of non-parametric measures for 8 maize hybrids yield stability assessment.

<table>
<thead>
<tr>
<th>Cultivars</th>
<th>Yield $t$ ha$^{-1}$</th>
<th>Kang</th>
<th>$S_i^1$</th>
<th>Hühn</th>
<th>$S_i^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aster</td>
<td>10.54</td>
<td>7</td>
<td>2.43</td>
<td>4.51</td>
<td></td>
</tr>
<tr>
<td>ES Paroli</td>
<td>10.48</td>
<td>6</td>
<td>2.73</td>
<td>5.72</td>
<td></td>
</tr>
<tr>
<td>Coxximo</td>
<td>10.44</td>
<td>5</td>
<td>2.24</td>
<td>3.89</td>
<td></td>
</tr>
<tr>
<td>MAS 25A</td>
<td>10.42</td>
<td>12</td>
<td>2.94</td>
<td>6.98</td>
<td></td>
</tr>
<tr>
<td>Amadeo</td>
<td>10.40</td>
<td>10</td>
<td>2.00</td>
<td>2.92</td>
<td></td>
</tr>
<tr>
<td>Monumental</td>
<td>10.30</td>
<td>9</td>
<td>2.35</td>
<td>4.59</td>
<td></td>
</tr>
<tr>
<td>Silas</td>
<td>10.29</td>
<td>14</td>
<td>2.41</td>
<td>4.47</td>
<td></td>
</tr>
<tr>
<td>System</td>
<td>9.57</td>
<td>13</td>
<td>1.49</td>
<td>2.42</td>
<td></td>
</tr>
</tbody>
</table>
parametric and non-parametric hybrid stability evaluation

Table 3 - Mean yields and assessment of agronomic stability of maize hybrids by the method of homogeneous groups ranks (RD).

<table>
<thead>
<tr>
<th>Cultivars</th>
<th>Yield 1 ha$^{-1}$</th>
<th>Rank RD</th>
<th>Coefficient of variability (CV)</th>
<th>Percentage of environments where the cultivar rank 1, 2, 3, remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asteri</td>
<td>10.54</td>
<td>1.67</td>
<td>19.69</td>
<td>48 41 7 4</td>
</tr>
<tr>
<td>ES Paroli</td>
<td>10.48</td>
<td>1.89</td>
<td>20.13</td>
<td>44 30 19 7</td>
</tr>
<tr>
<td>Coxximo</td>
<td>10.44</td>
<td>1.89</td>
<td>17.23</td>
<td>37 37 26 0</td>
</tr>
<tr>
<td>MAS 25A</td>
<td>10.42</td>
<td>1.89</td>
<td>19.18</td>
<td>44 33 11 11</td>
</tr>
<tr>
<td>Amadeo</td>
<td>10.40</td>
<td>1.85</td>
<td>18.14</td>
<td>37 41 22 0</td>
</tr>
<tr>
<td>Monumental</td>
<td>10.30</td>
<td>2.07</td>
<td>18.85</td>
<td>30 44 15 11</td>
</tr>
<tr>
<td>Silas</td>
<td>10.29</td>
<td>2.07</td>
<td>17.36</td>
<td>52 11 19 19</td>
</tr>
<tr>
<td>System</td>
<td>9.57</td>
<td>2.89</td>
<td>17.28</td>
<td>7 33 33 26</td>
</tr>
</tbody>
</table>

where:

$D_i = \left( \sum_{j=1}^{N} \left( \hat{r}_{ij} - \bar{r}_i \right) \right)^{1/2} : \hat{r}_{ij} = \left( x_{ij} + x_{i..} - x_{j..} \right)$

Non-parametric methods

1. Hühn’s stability measures (1990)

Two stability measures have been applied:

(1) $S_i^2 = \frac{\sum \left| r_j - r_{ij}' \right|^2}{N(N-1)}$

where: $r_j = \text{rank of the } j\text{th genotype in the } j\text{th environment}; r_{ij}' = \text{rank based on the corrected values of } x_{ij}; N = \text{number of environments}; x_{ij}' = x_{ij} - x_{i..} - x_{j..}.$

(2) $S_{ij}^2 = \frac{\sum \left( r_j - \bar{r}_j \right)^2}{N-1}$

where: $\bar{r}_j = \sum r_j / N; \bar{r}_i = \text{mean rank for the } i\text{th genotype.}$


This method combines cultivar yield and Shukla’s stability variance into one statistic. The variety with the highest yield is given a rank of 1, while that of the lowest variance is also assigned a rank of 1. The ranks for yield and variance are summed up. The cultivar having the lowest rank sum is the most desirable.

3. New method based on ranks of homogeneous groups (RD) and coefficient of variability (CV).

After performing analysis of variance of single experiments for each location and year, the null hypothesis was verified using F test. After rejecting the null hypothesis Haufe and Geidel test was used for multiple comparisons of cultivar means.

Cultivars belonging to the same homogeneous groups were given identical rank. After summing up all ranks for particular cultivars, the mean overall rank (RD) was computed for each cultivar.

Haufe and Geidel test separates means into distinct homogeneous groups which do not overlap. The general formula for the test is as follows:

$GD = S_\alpha \times T(\alpha; p, k, FG)$

where: $S_\alpha = \text{standard error of a treatment mean}; \alpha = \text{level of significance}; p = \text{number of means under comparison}; k = \text{number of means compared within a group}; FG = \text{degrees of freedom for error mean square in analysis of variance}; T = \text{tabular value of t.}$

When we adopt the critical difference as:

$GD_1 = S_\alpha \times T(\alpha; p, k, FG) / \sqrt{n}; n = \text{number of replications}$

we get:

$S_\alpha = \sqrt{\frac{S^2_{\alpha}}{n} + \frac{S^2_{\alpha}}{nk}}$

Thanks to the correction, we arrive at the modification as follows:

Table 4 - Spearman’s rank correlations between parametric and nonparametric stability measures for grain yield.

<table>
<thead>
<tr>
<th>Measures</th>
<th>$b_i$</th>
<th>$S^2_{ai}$</th>
<th>Hanson</th>
<th>Wricke</th>
<th>Shukla</th>
<th>Kang</th>
<th>Hühn $S^1_i$</th>
<th>Hühn $S^2_i$</th>
<th>$R_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain yield</td>
<td>0.82*</td>
<td>0.10</td>
<td>0.76*</td>
<td>0.04</td>
<td>0.04</td>
<td>-0.68</td>
<td>-0.57</td>
<td>-0.48</td>
<td>0.86*</td>
</tr>
<tr>
<td>$S^2_{ai}$</td>
<td>0.02</td>
<td>0.86*</td>
<td>0.98*</td>
<td>0.98*</td>
<td>0.76*</td>
<td>0.59</td>
<td>0.42</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Hanson</td>
<td>0.31</td>
<td>0.98*</td>
<td>0.63</td>
<td>-0.40</td>
<td>-0.47</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wricke</td>
<td>1.00</td>
<td>0.73*</td>
<td>0.62</td>
<td>0.45</td>
<td>0.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shukla</td>
<td></td>
<td>0.73*</td>
<td>0.61</td>
<td>0.45</td>
<td>0.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kang</td>
<td></td>
<td></td>
<td>0.07</td>
<td>0.10</td>
<td>0.66</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hühn $S^1_i$</td>
<td></td>
<td></td>
<td>0.92*</td>
<td>-0.52</td>
<td>-0.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hühn $S^2_i$</td>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>
After calculation – with the use of the correction coefficient $\frac{k+1}{2k}$ – of GD, as a value of the least significant difference (NIR), the following formula for the critical value is obtained:

$$GD = GD \times \sqrt{\frac{k+1}{2k}}$$

Compute the observed difference $D_i = x_1 - x_2$ and compare it with GD$_i$ value. If $D_i > GD_i$, the cultivars are assigned to separate groups. If $D_i < GD_i$, the cultivars are in the same group. Next, calculate the difference:

$$D_2 = \frac{(x_1 + x_2)}{2}$$

and compare with the corrected GD$_i$ value. The procedure is continued until all comparisons are made. In the end we obtain non overlapping groups of treatment means.

**Results**

Analyses of variance have revealed significant variability between the cultivars, locations, years and significant GxE interactions.

Table 1 shows the estimation of yield stability by four parametric methods. According to Eberhart and Russell method the most stable cultivars were Coxximo and Amadeo and they also had average adaptability to environmental conditions. Hybrid ES Paroli was less stable and tended to be better adapted to more favourable environments whereas hybrid System showed adaptedness to lower yielding environments.

$D_i$ values of Hanson pointed to the highest yielding cultivars Es Paroli and Asteri as the most stable. The lowest yielding hybrid System was the least stable.

Because Shukla’s stability variance is a linear combination of the ecovalence so for ranking purposes these methods are equivalent. It can be seen from Table 1 that cultivars Amadeo and Coxximo were the most stable. The least stable cultivar was Mass 25A.

Table 2 shows non-parametric measures of stability estimated according to Hühn and Kang. Two Hühn’s parameters $S_1$ and $S_2$ gave similar ranking of cultivars. The lowest yielding hybrid System was the most stable-followed by high yielding Amadeo and Coxximo.

According to Kang’s rank sum method Coxximo, Amadeo and ES Paroli were the most stable and desirable cultivars while lower yielding Silas and System were the least stable.

$R\_b$ values computed according to the new method are presented in Table 3. The lowest $R\_b$ values indicate the cultivars which perform best and are characterized by high stability. Top ranking cultivar Asteri was the highest yielder. Cultivars ES Paroli, Coxximo, Mas 25A and Amadeo obtained the same rank although they differed in regard to percentage of environments in which they occurred in particular homogenous groups. In order to get more information about stability and desirability of a cultivar, $R\_b$ values should be combined with coefficient of variability. Figure 1 shows $R\_b$ values plotted against coefficient of variability. Cultivar Coxximo in the upper left quadrant is the most desirable due to its performance and stability. Cultivar Silas is also stable but its performance is below over all treatment mean. Cultivars Asteri, Mas 25A and ES Paroli are high yielding but below average stability as measured by coefficient of variability.

Rank correlation between pairs of parametric and non-parametric measures are presented in Table 4. Significant correlations were found between mean yield and two parametric measures $b_i$ and $D_i$. Of non-parametric statistics only $R\_b$ was significantly associated with yield ($r=0.86$) whereas Kang’s rank sum just missed significance ($r=0.68$). Wricke’s ecovalence...
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(W) and deviation from regression (S_i^2_d) were very highly correlated (r = 0.98). Full correlation was found between Wricke’s and Shukla’s statistics. Hühn’s stability measures S_1^2 and S_2^2 were highly positively associated (r = 0.92).

Discussion

Both parametric and non-parametric measures of stability, with the exception of Hanson method, indicated either Amadeo or Coximno as the most stable hybrids. This unusual consistency not found in other studies (Mohammadi et al., 2007; 2008) may be due to relatively small number of hybrids which were high yielding and their regression coefficients were close to 1.

Overall however, only b, D, and R were significantly correlated with yield. Significant negative association between bi and yield was also found by Mohammadi et al. (2008). There was no significant correlation between Hühn’s stability measures S_1^2, S_2^2, and yield. Similar results were also reported in durum wheat (Mohammadi et al., 2007; 2008), winter wheat (Mohammadi et al., 2007), and lentil (Sabaghnia at al., 2006). Strong correlation (r=0.98) between S_2^2 and Wricke’s ecovalence was observed, but these parameters were not significantly associated with yield. Similar findings were reported by Mohammadi et al. (2008). In stability studies either S_2^2 or Shukla’s stability variance or Wricke’s ecovalence can be used.

Numerous methods have been developed to analyse phenotypic stability which implies they all have their limitations and there is no superior method to be recommended in all circumstances. The new proposed method based on homogenous groups is strongly correlated with yield and can be a useful alternative to Kang’s rank sum or Fox’es stratified ranking technique in studies of agronomic stability of maize hybrids.

References
