Nonparametric measures of phenotypic stability. Part 2: Applications

Manfred Huehn
Institute of Crop Science and Plant Breeding, University of Kiel, Olshausenstrasse 40, D-2300 Kiel, FRG

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Summary

The three nonparametric measures of phenotypic stability $S_1$, $S_2$, and $S_3$ introduced and discussed in Huehn (1990) and the classical parameters: environmental variance, ecovalence, regression coefficient, and sum of squared deviations from regression were computed for winter wheat grain yield data from the official registration trials (1974, 1975, and 1976) in the Federal Republic of Germany.

The similarity of the resulting stability rank orders of the genotypes which are obtained by applying different stability parameters were compared using rank correlation coefficients. The correlations between each of $S_1$, $S_2$, and $S_3$ and the classical stability parameters were different in sign and very low for regression coefficient and environmental variance, but positive and medium for ecovalence and sum of squared deviations from regression (except $S_1$ in 1976). The differences between the correlations for the 3 years were considerable.

The parameters $S_1$ and $S_2$ were very strong intercorrelated with each other with a good agreement of the correlations for the different years. The divergent property of $S_3$ can be explained by its modified definition (confounding of stability and yield level).

The previous results and conclusions obtained from the stability analysis of the original uncorrected data $x_{ij}$ are further strengthened if one uses corrected values $x_{ij}^* = x_{ij} - (\bar{x}_i - \bar{x})$. The nonparametric stability measures were nearly perfectly associated (even with $S_3$ included) which, of course, implies no significant differences between the correlations of the different years.

For the correlations between each of the $S_1$, $S_2$, and $S_3$ and the classical parameters, very low values were obtained for regression coefficient and environmental variance, but relatively large values for ecovalence and sum of squared deviations from regression.

The differences between the correlations for the different years are low for ecovalence and sum of squared deviations from regression with each of $S_1$, $S_2$, and $S_3$, but these differences are large for regression coefficient and environmental variance. This transformation $x_{ij} \rightarrow x_{ij}^*$ reduced individual and global significances (stability of single genotypes and stability differences between all the tested genotypes) drastically. The significant results for the transformed data indicate a very reliable quantitative characterization of the stability of the genotypes independent from the yield level.
Introduction

An analysis of genotype x environment interactions as well as an estimation of phenotypic yield stability has been intensively discussed in the last two decades.

In the first part of this paper (Huehn, 1990) three nonparametric measures of phenotypic stability were proposed. These stability statistics are based on the ranks of genotypes in the different environments. For a general discussion of the advantages of nonparametric measures compared to the common parametric statistics which are based on the absolute yield data we refer to Huehn (1990). An extensive list of references on these topics are cited in this publication and are not be repeated here.

In a two-way table with K rows (genotypes) and N columns (environments) the phenotypic values $X_{ij}$ are ranked within each column = environment separately ($X_{ij} =$ phenotypic value of the i th genotype in the j th environment with $i = 1, 2, \ldots, K$ and $j = 1, 2 \ldots, N$). Let $r_{ij}$ be the rank of genotype i in environment j.

In Huehn (1990) the following concept of stability was applied: A genotype i is stable over environments if its ranks are similar over environments. Three different statistics $S^{(1)}$, $S^{(2)}$ and $S^{(3)}$ measuring the similarity of the ranks for each row = genotype have been proposed and discussed. Each can be used as a stability parameter (Huehn, 1990).

Furthermore, the following transformation of the original data was proposed: $x_{ij}^* = x_{ij} - (\bar{x}_i - \bar{x})$ where $\bar{x}_i =$ marginal mean of genotype i and $\bar{x} =$ overall mean in the $K \times N$ table. In this case the stability measures $S^{(1)}$, $S^{(2)}$ and $S^{(3)}$ may be calculated by using the ranks based on the transformed values $x_{ij}^*$.

Approximate tests of significance based on the normal distribution were developed by Nassar and Hühn (1987) for two of these nonparametric measures: for the ‘mean absolute rank difference’ and for the ‘variance of the ranks’.

For an efficient use of stability estimation techniques in practical applications knowledge on the following aspects is essential:

1. Relations between different statistical measures of phenotypic stability (parametric and nonparametric).
2. Consistency of relationships among stability parameters.
3. Repeatability of stability parameters.

For the common parametric measures of phenotypic stability many investigations have been published dealing with relations between the parameters – see Léon (1985) and Lin et al. (1986). Less publications exist for the nonparametric measures, but, some recent studies are available reporting results on 1) relations among the nonparametric measures and on 2) relations between parametric and nonparametric stability statistics (Hühn, 1979; Hühn, 1981; Skrøppa, 1984; Léon, 1985; Böhm & Schuster, 1985; Hühn & Léon, 1985; Magnussen & Yeatman, 1986; Clair & Kleinschmit, 1986; Becker, 1987; Wanyancha & Morgenstern, 1987; Becker & Léon, 1988; Léon & Becker, 1988). References for the repeatability topic are given in part 1 of this paper (Huehn, 1990).

This paper presents some applications of the theoretical concepts and approaches from Huehn (1990). In addition, relationships between the nonparametric and parametric measures of stability and consistency of relationships are examined.

Materials and methods

Winter wheat data from the official registration trials (‘Wertprüfung II, Sortiment A, Durchschnitt Stufe 1 und 2’) in the Federal Republic of Germany in 1974, 1975 and 1976 were analysed for grain yield. Only those genotypes with yields available for all the locations were included in the calculations. These numbers were: 42 genotypes and 15 locations in 1974, 38 genotypes and 12 locations in 1975, and 46 genotypes and 13 locations in 1976. The exact composition of the set of tested genotypes changed from year to year.

Of main interest in this paper are 1) the similarity of the resulting stability rank orders of the genotypes for different measures of stability and 2) the agreement of these relations for the different years.

In addition to the proposed nonparametric sta-
bility measures $S^{(1)}$, $S^{(2)}$ and $S^{(3)}$ some of the classical stability parameters were included: variance of the $x_{ij}$ of the genotype $i$ (environmental variance); ecovalence (contribution of genotype $i$ to the total genotype × environment interaction sum of squares (Wricke, 1962)); and the regression coefficient and sum of squared deviations from regression (regression of the mean yield of each genotype in the different environments on the respective means of all genotypes under test (Eberhart & Russell, 1966)). In applying the regression approach we use the stability concept of: maximum stability = regression coefficient of zero and sum of squared deviations from regression of zero.

Instead of ordinary coefficients of correlation, Spearman’s rank correlations were calculated among the rank orders based on these 7 stability parameters. Tests of significance for these rank correlations were performed in the usual way (Sachs, 1969).

For the given numerical examples of the winter wheat data sets both uncorrected data $x_{ij}$ as well as corrected values $x^*_i$ were examined.

The original yield data for 1974, 1975, and 1976 as well as the numerical values of the different stability parameters are not presented here, but can be obtained on request from the author.

Tests of significance are available for the non-parametric measures

\[ S^{(1)} = 2 \sum_{i < j'} \left| r_{ij} - r_{ij'} \right| / N (N - 1) \]

\[ S^{(2)} = \sum_{i = 1}^{N} (r_{ij} - \bar{r}_i)^2 / (N - 1) \]

(Nassar & Hühn, 1987; Huehn, 1990). The results for testing the individual $Z_i^{(1)}$ and $Z_i^{(2)}$ for each $i$, $i = 1, 2, \ldots, K$, (see: Huehn, 1990) by the chi-squared distribution with 1 degree of freedom are not presented here, but can be obtained on request from the author.

In this paper only the percentages $\Delta$ of significant $Z_i^{(1)}$ and $Z_i^{(2)}$ among the tested genotypes are presented and discussed. In this publication only the results for the global tests of significance for testing differences in stability between all the genotypes by applying the statistics $S^{(1)}$ and $S^{(2)}$ (see: Huehn, 1990) for a chi-squared distribution with K degrees of freedom are presented.

Results and discussion

A. Noncorrected data

In all the years the correlations between the regression coefficient and each of the proposed stability parameters $S^{(1)}$, $S^{(2)}$ and $S^{(3)}$ are different in sign and, additionally, very low ($\leq 0.10$ for $S^{(1)}$ and $S^{(2)}$) — with a slight exception for $S^{(3)}$ (all correlations

<table>
<thead>
<tr>
<th>Year</th>
<th>envir. var.</th>
<th>ecovalence</th>
<th>regress. coeff.</th>
<th>sum of squared dev. from regr.</th>
<th>$S^{(1)}$</th>
<th>$S^{(2)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>0.28</td>
<td>0.46**</td>
<td>0.10</td>
<td>0.40*</td>
<td>0.55**</td>
<td>0.28</td>
</tr>
<tr>
<td>1975</td>
<td>0.34*</td>
<td>0.57**</td>
<td>0.06</td>
<td>0.58**</td>
<td>0.98**</td>
<td>0.37*</td>
</tr>
<tr>
<td>1976</td>
<td>-0.03</td>
<td>0.40**</td>
<td>-0.10</td>
<td>0.49**</td>
<td>0.97**</td>
<td>0.30*</td>
</tr>
<tr>
<td>1974</td>
<td>0.26</td>
<td>0.52**</td>
<td>0.06</td>
<td>0.45**</td>
<td>-</td>
<td>0.33*</td>
</tr>
<tr>
<td>1975</td>
<td>0.37*</td>
<td>0.61**</td>
<td>0.04</td>
<td>0.61**</td>
<td>-</td>
<td>0.42*</td>
</tr>
<tr>
<td>1976</td>
<td>-0.01</td>
<td>0.44**</td>
<td>-0.08</td>
<td>0.50**</td>
<td>-</td>
<td>0.28</td>
</tr>
<tr>
<td>1974</td>
<td>-0.28</td>
<td>0.38</td>
<td>-0.47**</td>
<td>0.39</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1975</td>
<td>-0.08</td>
<td>0.72**</td>
<td>-0.49**</td>
<td>0.72</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1976</td>
<td>-0.42**</td>
<td>0.15</td>
<td>-0.46**</td>
<td>-0.23</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* = Significance for an error probability of 0.05 or 0.01 respectively.
negative between 0.46 and 0.49) (Table 1). These correlations between regression coefficient and $S_l^{(3)}$ are also very similar in their numerical values for the different years (high consistency of these correlations (Table 1).

The correlations between the environmental variance and each of the parameters $S_l^{(1)}$, $S_l^{(2)}$ and $S_l^{(3)}$ are different in sign for the different years and they are also very low ($\leq 0.42$) (Table 1). These correlations between regression coefficient as well as environmental variance and each of $S_l^{(1)}$, $S_l^{(2)}$ and $S_l^{(3)}$ in most situations are not statistically significant.

The correlations between covariation as well as sum of squared deviations from regression with each of the parameters $S_l^{(1)}$, $S_l^{(2)}$ and $S_l^{(3)}$ are positive (with only one exception: $S_l^{(3)}$ in 1976) and medium in size with numerical values from 0.38 to 0.72 (excluding $S_l^{(3)}$ in 1976) (Table 1). Most of these correlations are highly significant.

The differences among the correlations between the classical stability parameters and the proposed nonparametric measures (left part of Table 1) for the three years are considerable.

The parameters $S_l^{(1)}$ and $S_l^{(2)}$ are nearly perfectly associated in 1975 and 1976 while in 1974 this correlation is intermediate.

The correlations between $S_l^{(1)}$ and $S_l^{(3)}$ as well as the correlations between $S_l^{(2)}$ and $S_l^{(3)}$ are all positive and low. But, nevertheless, most of them are statistically significant. Both correlations are very similar in numerical magnitude (0.30–0.40). The numerical values of the correlation coefficients for the different years are quite similar for both correlations (Table 1).

This divergent property of $S_l^{(3)}$ may be caused by its modified definition (confounding and simultaneous consideration of stability and yield) and has been discussed in part 1 (Huehn, 1990).

The results of the tests of significance are given in the left part of Table 5: For each year the test statistic $S_l^{(1)}$ as well as the test statistic $S_l^{(2)}$ are highly significant with considerable differences of their numerical values in the different years. $S_l^{(3)}$ is always markedly larger than $S_l^{(2)}$. The same is true for the corresponding $\Delta$-values which are in the range of 50–70% for $S_l^{(1)}$ and 35–50% for $S_l^{(2)}$ (Table 5).

Summarizing these results on the analysis of the noncorrected data $x_{ij}$ one may conclude: The approximate agreement of the correlations among the nonparametric measures $S_l^{(1)}$, $S_l^{(2)}$ and $S_l^{(3)}$ (right part of Table 1) in the different years (high consistency of these correlations) indicates that these numerical results reflect some generally valid relations between the different stability parameters. Furthermore, $S_l^{(1)}$ and $S_l^{(2)}$ often lead to nearly identical stability rank orders while $S_l^{(3)}$ produces quite different rank orders.

The relatively low correlation coefficients between each of $S_l^{(1)}$, $S_l^{(2)}$ and $S_l^{(3)}$ and the classical

<table>
<thead>
<tr>
<th>envir. var.</th>
<th>ecovalence</th>
<th>regress. coeff.</th>
<th>sum of squared dev. from regr.</th>
<th>$S_l^{(2)}$</th>
<th>$S_l^{(3)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_l^{(1)}$</td>
<td>1974</td>
<td>0.58**</td>
<td>0.88**</td>
<td>0.35*</td>
<td>0.83**</td>
</tr>
<tr>
<td></td>
<td>1975</td>
<td>0.20</td>
<td>0.90**</td>
<td>-0.30</td>
<td>0.88**</td>
</tr>
<tr>
<td></td>
<td>1976</td>
<td>0.03</td>
<td>0.70**</td>
<td>-0.03</td>
<td>0.71**</td>
</tr>
<tr>
<td>$S_l^{(2)}$</td>
<td>1974</td>
<td>0.57**</td>
<td>0.88**</td>
<td>0.34*</td>
<td>0.83**</td>
</tr>
<tr>
<td></td>
<td>1975</td>
<td>0.21</td>
<td>0.90**</td>
<td>-0.30</td>
<td>0.80**</td>
</tr>
<tr>
<td></td>
<td>1976</td>
<td>0.03</td>
<td>0.71**</td>
<td>-0.03</td>
<td>0.71**</td>
</tr>
<tr>
<td>$S_l^{(3)}$</td>
<td>1974</td>
<td>0.55**</td>
<td>0.76**</td>
<td>0.35*</td>
<td>0.69**</td>
</tr>
<tr>
<td></td>
<td>1975</td>
<td>0.16</td>
<td>0.75**</td>
<td>-0.16</td>
<td>0.74**</td>
</tr>
<tr>
<td></td>
<td>1976</td>
<td>0.11</td>
<td>0.53**</td>
<td>0.06</td>
<td>0.57**</td>
</tr>
</tbody>
</table>

* , ** = Significance for an error probability of 0.05 or 0.01 respectively.
stability parameters (especially for the regression coefficient and the environmental variance) demonstrate that the proposed nonparametric stability measures use other information from the original yield data \( x_{ij} \) (left part of Table 1).

Furthermore, these correlations are quite different in the different years (low consistency of these correlations).

### B. Corrected data

In all the years correlations between the regression coefficient and each of the proposed stability parameters \( S^{(1)} \), \( S^{(2)} \) and \( S^{(3)} \) are different in sign and, additionally, very low (less than 0.35) (Table 2). Correlations between the environmental variance and each of the proposed parameters \( S^{(1)} \), \( S^{(2)} \) and \( S^{(3)} \) are positive throughout and they are medium (in 1974) or low (in 1975 and 1976) (Table 2). Correlations between regression coefficient as well as environmental variance and each of \( S^{(1)} \), \( S^{(2)} \) and \( S^{(3)} \) are significant only for 1974.

All the correlations between ecovalence as well as sum of squared deviations from regression with each of the parameters \( S^{(1)} \), \( S^{(2)} \) and \( S^{(3)} \) are positive and highly significant and medium or large in size with numerical values from 0.53 to 0.90 (Table 2). This implies that for corrected yield data \( x_{ij}^{*} \) the ecovalence as well as the sum of squared deviations from regression (both are usually highly correlated) lead to similar rank orders of the genotypes than the nonparametric measures \( S^{(1)} \), \( S^{(2)} \) and \( S^{(3)} \).

The differences among the correlations between the classical stability parameters and the proposed nonparametric measures (left part of Table 2) for the three years are considerable for environmental variance and regression coefficient (low consistency of these correlations), but these differences are low for ecovalence and sum of squared deviations from regression (high consistency of these correlations).

Furthermore, the correlations between each of the classical stability parameters with the different new measures \( S^{(1)} \), \( S^{(2)} \) and \( S^{(3)} \) are very similar if they were considered for each year separately. These results are summarized in Table 3: We find small differences for the same year using the different measures \( S^{(1)} \), \( S^{(2)} \) and \( S^{(3)} \) where \( S^{(1)} \) and \( S^{(2)} \) show nearly identical results while \( S^{(3)} \) deviates slightly.

The parameters \( S^{(1)} \), \( S^{(2)} \) and \( S^{(3)} \) are nearly perfectly correlated among each other. All coefficients are highly significant with numerical values between 0.89 and 1.00. Thus, of course, the agreement of these correlation coefficients for the different years must be also extremely good (right part of Table 2) (high consistency of these correlations).

These extremely high intercorrelations among the \( S^{(1)} \), \( S^{(2)} \) and \( S^{(3)} \) confirm the previous results of the similar correlations between each of the classical stability parameters with the different nonparametric measures for a given year (Table 3). Thus we can conclude: If we proceed from the corrected data \( x_{ij}^{*} \) in an analysis of phenotypic stability each of the nonparametric measures \( S^{(1)} \), \( S^{(2)} \) and \( S^{(3)} \) can be used as an appropriate stability parameter because they lead to nearly identical stability rank orders of the genotypes.

The results of the tests of significance are presented in the right part of Table 5: The test statistic \( S^{(1)} \) is not significant for 1974 and 1976 while \( S^{(2)} \) is

### Table 3. Correlations between the 'classical' stability parameters with each of the nonparametric measures \( S^{(1)} \), \( S^{(2)} \) and \( S^{(3)} \) in 1974, 1975 and 1976 using the corrected data \( x_{ij}^{*} \)

<table>
<thead>
<tr>
<th></th>
<th>environmental variance</th>
<th>sum of squared deviations from regression</th>
<th>ecovalence</th>
<th>regression coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>0.58</td>
<td>0.20</td>
<td>0.03</td>
<td>0.83</td>
</tr>
<tr>
<td>1975</td>
<td>0.57</td>
<td>0.21</td>
<td>0.03</td>
<td>0.83</td>
</tr>
<tr>
<td>1976</td>
<td>0.55</td>
<td>0.16</td>
<td>0.11</td>
<td>0.69</td>
</tr>
</tbody>
</table>
Table 4. Rank correlations between the two stability rank orders of the genotypes obtained by using the uncorrected yield data $x_{ij}$ and by using the corrected values $x_{ij}^*$

<table>
<thead>
<tr>
<th>Year</th>
<th>Nonparametric measures</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S^{(1)}$</td>
<td>$S^{(2)}$</td>
</tr>
<tr>
<td>1974</td>
<td>0.50</td>
<td>0.54</td>
</tr>
<tr>
<td>1975</td>
<td>0.61</td>
<td>0.64</td>
</tr>
<tr>
<td>1976</td>
<td>0.44</td>
<td>0.41</td>
</tr>
</tbody>
</table>

not significant for 1974. The differences between the numerical values of $S^{(1)}$ as well as of $S^{(2)}$ in the different years are considerable. $S^{(1)}$ is always smaller than $S^{(2)}$—but both values are not too much different from each other (in each year). The same is true for the corresponding $\Delta$-values which are in the range of 5–20% for both $S^{(1)}$ and $S^{(2)}$ (Table 5).

C. Corrected vs. uncorrected data

In part 1 of this paper (Huehn, 1990) some comments are given on the meaning and the resulting effects of the transformation of the $x_{ij}$ into the $x_{ij}^*$. Additionally, it shall be mentioned here that the numerical values of each of the classical stability parameters: environmental variance, ecovariance, regression coefficient and sum of squared deviations from regression are identical for the original untransformed yield data $x_{ij}$ and for the transformed values $x_{ij}^*$. Therefore, this transformation has an effect only on the nonparametric measures and their resulting rank orders. This comment, of course, is of essential importance for an interpretation and comparison of the correlation results in the left part of Table 1 and in the left part of Table 2.

In this section the effects of the transformation of the original yield data $x_{ij}$ into the corrected values $x_{ij}^*$ shall be investigated quantitatively: The resulting stability rank orders of the genotypes which are obtained by using the uncorrected yield data $x_{ij}$ and by using the corrected values $x_{ij}^*$ are quite different. The rank correlation coefficients between these two rank orders are presented in Table 4. They are medium or low with considerable differences between the three years (Table 4).

The large effects of the transformation $x_{ij} \rightarrow x_{ij}^*$ can be also demonstrated by looking at the results of the tests of significance in Table 5: The numerical values of the test statistic $S^{(1)}$ are much larger (in all years) with uncorrected data compared to the values obtained with corrected data: uncorrected: corrected = 4.1, 3.4 and 6.4 respectively.

The same is true for the test statistic $S^{(2)}$, but with less pronounced differences: uncorrected: corrected = 2.5, 1.8 and 3.0 respectively.

The $\Delta$-values indicate much more significant individual stability parameter values for the uncorrected data compared to the corrected data. This is true for both stability statistics $S^{(1)}$ and $S^{(2)}$ (Table 5).

The results of Table 5 clearly demonstrate the large effects of the transformation of the original yield data $x_{ij}$ into the $x_{ij}^*$, which are the yields adjusted for the effects of genotypes (Huehn, 1990). This transformation reduces individual significances (significances based on the individual $Z^{(1)}$ and

Table 5. Numerical values of the test statistics $S^{(1)}$ and $S^{(2)}$ together with the percentages $\Delta$ of significant individual $Z^{(1)}$ and $Z^{(2)}$ respectively for both the uncorrected and the corrected data

<table>
<thead>
<tr>
<th>year</th>
<th>Application of the uncorrected data $x_{ij}$</th>
<th></th>
<th>Application of the corrected data $x_{ij}^*$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S^{(1)}$</td>
<td>$\Delta$</td>
<td>$S^{(2)}$</td>
<td>$\Delta$</td>
</tr>
<tr>
<td>1974</td>
<td>199.91**</td>
<td>47.6</td>
<td>135.92**</td>
<td>35.7</td>
</tr>
<tr>
<td>1975</td>
<td>257.99**</td>
<td>55.3</td>
<td>158.20**</td>
<td>44.7</td>
</tr>
<tr>
<td>1976</td>
<td>368.15**</td>
<td>69.6</td>
<td>218.51**</td>
<td>50.0</td>
</tr>
</tbody>
</table>

*, ** = Significance for an error probability of 0.05 or 0.01 respectively.
Z(I) and global significances (significances for differences in stability between all the genotypes) drastically. These remaining significances for the corrected data may be considered to be of high reliability if one is interested in a characterization of the stability of the genotypes independent from the yield level.

Based on the results of Table 5 a final comment shall be mentioned: S(I) > S(2) (in each year) for uncorrected data xij and S(I) < S(2) (in each year) for corrected data xij*. In common applications we are mainly interested in the analysis of xij* (estimation of yield stability independent from yield level). Application of S(I), therefore, is a conservative test procedure. With our inferences on stability we are on the safe side.

Conclusions and recommendations

The main results of these investigations can be summarized as follows:
1. An analysis of phenotypic stability should be performed by using corrected data xij* if one wants to estimate the phenotypic stability independent from yield level effects.
2. For a quantitative estimation of phenotypic stability the nonparametric measure S(I) is preferable (= mean absolute rank difference). This measure is easy to calculate and to interprete. For this parameter an efficient test of significance is available.
3. If one is interested in a simultaneous consideration of both stability and yield the nonparametric stability parameter S(3) can be applied, which measures stability in units of yield. But, such an analysis, of course, must be performed by using the original noncorrected yield data xij because the transformation xij → xij* eliminates the genotypic effects from the data.

References


