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# Comparison of models for analysis of cultivar phenotypic stability

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## ABSTRACT

An analysis of the phenotypic stability of the yield of a group of 33 maize cultivars assessed in 19 locations in Rio Grande do Sul, was carried out with a non-linear model, the Gompertz growth curve. Five linear models were adjusted for comparison with each other and with the non-linear model, which was used as the control. Four of the linear models assessed were segmented in different ways and one, a model of quadratic regression, was continuous. The discontinuous bi-segmented model (Storck, Doctoral Thesis, ESALQ, USP, Piracicaba, SP, 1989) was considered the best because: a) it showed independence between the angles of the two segments; b) the hypothesis tests for the second segment are independent of the discontinuity; c) the estimated values adjust well to the Gompertz growth curve; d) the estimates of the parameters are more disperse. The model also fits better in a wide range of situations, over a complete growth curve, over the first and the second halves of the curve and over the initial third and middle of the curve.

## INTRODUCTION

Stability analysis is a technique used to study the interaction of cultivars and environments (locations and/or years) used by plant breeders to assess cultivar behavior. The choice of the most suitable model for the stability analysis is of fundamental importance to identify the best cultivar.

Methods based on a large number of stability parameters are efficient for cultivar stability characterization (Oliveira, 1976). The regression and regression deviation method of Eberhart and Russell (1966) together with the mean provides good information about cultivar response to environmental change. Carvalho *et al.* (1983) concluded that models based on one or two parameters were less efficient for determining stability than methods with three parameters. They also concluded that, in general, higher yielding cultivars are more unstable.

When the regression deviation variance is large, as found by Carvalho *et al.* (1983), the linear model may not fit the data and a non-linear model may be more appropriate. A study by Perkins and Jinks (1968) came to a similar conclusion. They found significant positive and negative correlations between the linear regression residues for each pair of cultivars, indicating that there is no parallelism among the residues and therefore some cultivars show a non-linear response to the environmental variation.

Verma *et al.* (1978) stated that regression techniques (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966) do not present sufficient evidence that the mean and environmental sensitivity are inde-

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pendent characteristics. According to these methods, a cultivar with above average sensitivity has high productivity in good environments and undesirable low productivity in unfavorable environments. The authors defined the ideal cultivar as that with a relatively high productivity and stable response in poor environments and a capacity to respond positively to environmental improvements. Consequently, they suggested an alternative technique which adjusted two straight line segments separately, one for below average environments, and another for those above average, including the environment closest to the general average.

Silva and Barreto (1985) proposed the adjustment, for each cultivar, of a single regression model made from the two straight line segments joined at the point corresponding to the value of zero in the environmental index. The modification proposed by Cruz *et al.* (1989) resulted in independence between the angles of the two segments and their discontinuity.

The discontinuity parameter was added to the bi-segmented model by Storck (1989), maintaining the independence between the angles of the two segments. Corrections were worked out for the estimates and tests of hypothesis, due to the errors in the independent variables and their correlation withs the dependent variable error.

Another modification in segmentation (Fonseca Jr., 1987) and the quadratic regression model (Brasil and Chaves, 1988) compared with other models indicate that there is evidence that non-linear regression models can be very useful in explaining the interaction of cultivars with environments. Not all cultivars give a linear response to environmental variation. However, since there are interpretation difficulties for non-linear model parameters, linear models could be used instead without loss of information.

A comparison of the segmented and continuous linear models was made, in comparison with a non-linear model.

# MATERIAL AND METHODS

Data from 19 maize experiments, normal maturity group, from the state network of trials in Rio Grande do Sul, coordinated by Instituto de Pesquisas Agronômicas (IPAGRO) in the agricultural year 1987/88, were used. The 33 cultivars were planted in a Randomized Complete Block design, with four replications. The average grain yields (t/ha) of each cultivar in each location, and the residual and blocks mean squares from each location were determined.

In the analyses, $Y_{ij}$ was the average of the ith cultivar in the jth environment (location). The environmental index, calculated as $\hat{\tau}_j = \bar{Y}_{.j} - \bar{Y}_{..}$, was used as an independent variable to adjust the non-linear model (NLM), called the Gompertz growth curve (Croxton and Cowden, 1955) characterized for cultivar i as

$$E(Y_j) = KA^{B^{\hat{\tau}_j}}$$

The estimates of the parameters (K, A and B) of this model were obtained by an iterative process, using a macro in the GLIM (Generalized Linear Interactive Modelling) software (Healy, 1988).

The following linear models were also adjusted for each cultivar:

**Model 1** - Silva and Barreto model (SB), proposed by Silva and Barreto (1985)

$$Y_{ij} = \beta 0_i + \beta 1_i \hat{\tau}_j + \beta 2_i T2(\hat{\tau}_j) + \delta_{ij} + \varepsilon_{ij}$$

**Model 2** - Modified Silva and Barreto (MSB), according to Cruz *et al.* (1989)

$$Y_{ij} = \beta 0_i + \beta 1_i \hat{\tau}_j + \beta 2_i Tm(\hat{\tau}_j) + \delta_{ij} + \varepsilon_{ij}$$

**Model 3** - Discontinuous Bi-segmented model (DBS), proposed by Storck (1989)

$$Y_{ij} = \beta 0_i + \beta 1_i \hat{\tau}_j + \beta 2_i Z_j \hat{\tau}_j + \beta 3_i Z_j + \delta_{ij} + \varepsilon_{ij}$$

**Model 4** - Segmented model (FJ), proposed by Fonseca Jr. (1987)

$$Y_{ij} = \beta 0_i + \beta 1_i T1(\hat{\tau}_j) + \beta 2_i T2(\hat{\tau}_j) + \delta_{ij} + \varepsilon_{ij}$$

**Model 5** - Quadratic model (QM), proposed by Brasil and Chaves (1988)

$$Y_{ij} = \beta 0_i + \beta 1_i \hat{\tau}_j + \beta 2_i \hat{\tau}_j^2 + \delta_{ij} + \varepsilon_{ij}$$

$\beta 0_i$, $\beta 1_i$, $\beta 2_i$, and $\beta 3_i$ are the parameters estimated in models 1 to 5; $\delta_{ij}$ is the deviation from regression for the ith cultivar in the jth environment; $\varepsilon_{ij}$ is the error of the mean $Y_{ij}$ and

$$T1(\hat{\tau}_j) = \hat{\tau}_j, \text{ if } \hat{\tau}_j < 0 \text{ else } T1(\hat{\tau}_j) = 0$$

$$T2(\hat{\tau}_j) = \hat{\tau}_j, \text{ if } \hat{\tau}_j > 0 \text{ else } T2(\hat{\tau}_j) = 0$$

$$Z_j = 1, \text{ if } \hat{\tau}_j > 0 \text{ else } Z_j = 0$$

$$Tm(\hat{\tau}_j) = \hat{\tau}_j - mp, \text{ if } \hat{\tau}_j > 0 \text{ else } Tm(\hat{\tau}_j) = 0$$

where mp is the average of the positive environmental indexes.

The parameters $\beta0_i$, $\beta1_i$, $\beta2_i$ and $\beta3_i$ and the mean squares of the deviations from regression ($MSD_i$), the adjusted determination coefficient ($R^2$) and the tests of hypotheses H0:β1=1, H0:β2=0 (H0:β1+β2=1, for model 4) and H0:β3=0, were calculated for each of the models (1 to 5) and each cultivar.

Estimates of $Y_{ij}$ were obtained for the linear models (1 to 5) and for the NLM, for $\tau_j'$ varying in units corresponding to 1/100 of the variation interval observed in $\tau_j$. The estimated values were denominated $\hat{Y}_{ijn}$ for the ith cultivar at the podint $\tau_j'$, for the NLM and $\hat{Y}_{ijl}$ for the linear model of order 1 = 1, 2, 3, 4 and 5, respectively.

Taking the estimates from the NLM as standard responses, fittings of the models (1 to 5) were tried to choose that best adjusted to the NLM. The statistic "Average Quadratic Deviate" (AQD) of the ith cultivar for the 1 model was calculated by,

$$AQD_{il} = \sum_{j=i}^{100} (\hat{Y}_{ijl} - \hat{Y}_{ijn})^2 / 100.$$

To check the adequacy of the linear models (1 to 5) for more general situations, the values of the independent variable $\tau_j''$ were defined for 30 equidistant points (j = 1, 2, ..., 30), whose range varied from the smallest observed value to a maximum value corresponding to 70% of the assymtotic point (K) of the adjusted curve for the ith cultivar. Estimates for $Y_{ij}$ were calculated by NLM for each of these 30 points, resulting in new data for the adjustment of each of the linear models (1 to 5). This adjustment was carried out at different positions (k = 1, ..., 6) on the curve, defined by the width of variation of the independent variable:

- Position 1: all of the curve, j varying from 1 to 30;
- Position 2: the first half of the curve, j varying from 1 to 15;
- Position 3: the second half of the curve, j varying from 16 to 30;
- Position 4: the first third of the curve, j varying from 1 to 10;
- Position 5: the middle third of the curve, j varying from 11 to 20;
- Position 6: the final third of the curve, j varying from 21 to 30.

For the ith cultivar, kth position and the 1 linear model adjusted to the new data, the AQD statistic was calculated by

$$AQD_{ilk} = \sum_{j=i}^{100} (\hat{Y}_{ijlk} - \hat{Y}_{ijn})^2 / 100.$$

where $\hat{\tau}_j$ varies equidistantly for 100 points within the range of the considered k position.

# RESULTS AND DISCUSSION

The results of the variance analysis, not showed here, indicated a significant interaction between cultivars and environment. The environmental variances were also significant overall and within each of the cultivars. A stability analysis, by regression, using the environmental effect as an independent variable is therefore adequate for this group of experiments.

A wide variation in environmental effects was observed (between -2.4118 and 2.6030 t/ha). These were relatively equidistant, as is recommended for regression analyses.

Table I shows the estimates of the parameters of the non-linear model (NLM). There was great variability; the variation coefficients of the estimates of the cultivar parametes, mainly K and A were large. High determination coefficients (Table I) were also obtained, resulting from a good fit of the data to the model. The NLM adjusted for each of the 33 cultivars can be used as a standard to compare the different linear models. Also, these 33 cultivars are a good sample of the possible kinds of cultivar responses to environmental variations. The correlations among the estimates of K, A and B are not linear and, consequently, it is difficult to establish criteria for cultivar selection and/or for tests of hypotheses based on the parameters K, A and B. It was also observed that for the high K estimates, there some cultivars were positioned at the beginning of the growth curve, the contrary happening with low K values. Therefore, an easily interpretable linear model which relates functionally to the growth curve is required to substitute the NLM.

Table II shows the means, standard deviation and the coefficient of variation of the estimates of the parameters (β0, β1, β2, and β3), the deviation from regression mean squares and the determination coefficient for the five linear models. A comparison of the fittings of the linear models among each other and with the NLM can be made by comparing the significances of the tests of hypotheses, the capacity or discrimination among the cultivars and the deviation from regression mean squares (Table III).

In the test of hypotheses H0:β1=1, H0:β2=0 e H0:β3=0, at a 5% level of significance, it was found that:

**Table I** - Estimates of the parameters (K, A, B) of the Gompertz growth curve, the deviations from regression mean squares (MSD) and of the determination coefficient ($R^2$) for 33 maize cultivars.

| Cultivar | K | A | B | MSD | R |
|---|---|---|---|---|---|
| 1 | 11.852 | 0.3415 | 0.7700 | 0.2228 | 0.9192 |
| 2 | 12.735 | 0.3252 | 0.7604 | 0.2415 | 0.9290 |
| 3 | 9.742 | 0.4045 | 0.7299 | 0.0834 | 0.9671 |
| 4 | 13.374 | 0.3197 | 0.8174 | 0.1121 | 0.9467 |
| 5 | 12.157 | 0.3436 | 0.7834 | 0.1257 | 0.9498 |
| 6 | 6.434 | 0.7168 | 0.5539 | 0.1163 | 0.9453 |
| 7 | 109.202 | 0.0310 | 0.9266 | 0.1637 | 0.9181 |
| 8 | 36.613 | 0.0928 | 0.8844 | 0.2330 | 0.9051 |
| 9 | 8.477 | 0.3855 | 0.7342 | 0.1403 | 0.9281 |
| 10 | 108.844 | 0.0371 | 0.9357 | 0.3605 | 0.8676 |
| 11 | 7.705 | 0.5233 | 0.6457 | 0.2084 | 0.9262 |
| 12 | 6.381 | 0.6263 | 0.5566 | 0.2749 | 0.8934 |
| 13 | 6.582 | 0.5852 | 0.6154 | 0.4005 | 0.8379 |
| 14 | 4.876 | 0.7289 | 0.4725 | 0.4259 | 0.8114 |
| 15 | 9.158 | 0.4244 | 0.7114 | 0.1462 | 0.9447 |
| 16 | 8.775 | 0.3932 | 0.6919 | 0.2897 | 0.9022 |
| 17 | 8.995 | 0.3890 | 0.7610 | 0.2553 | 0.8613 |
| 18 | 14.102 | 0.3032 | 0.7870 | 0.1257 | 0.9604 |
| 19 | 10.155 | 0.4291 | 0.7343 | 0.2233 | 0.9231 |
| 20 | 29.864 | 0.1434 | 0.8819 | 0.2285 | 0.9091 |
| 21 | 12.175 | 0.3251 | 0.7940 | 0.3108 | 0.8769 |
| 22 | 11.524 | 0.3569 | 0.7498 | 0.1570 | 0.9483 |
| 23 | 24.365 | 0.1629 | 0.8659 | 0.0993 | 0.9591 |
| 24 | 10.987 | 0.3706 | 0.7579 | 0.3800 | 0.8685 |
| 25 | 6.607 | 0.6089 | 0.6339 | 0.1816 | 0.9070 |
| 26 | 29.619 | 0.1285 | 0.8854 | 0.2714 | 0.8771 |
| 27 | 10.783 | 0.3561 | 0.7628 | 0.0627 | 0.9739 |
| 28 | 20.137 | 0.1966 | 0.8641 | 0.0946 | 0.9527 |
| 29 | 6.530 | 0.6041 | 0.6243 | 0.1864 | 0.9103 |
| 30 | 16.427 | 0.2664 | 0.8616 | 0.1136 | 0.9335 |
| 31 | 6.504 | 0.6925 | 0.5513 | 0.3109 | 0.8767 |
| 32 | 7.685 | 0.5406 | 0.6818 | 0.1485 | 0.9306 |
| 33 | 10.338 | 0.3886 | 0.7582 | 0.4102 | 0.8446 |
| Mean | 18.446 | 0.3805 | 0.7438 | 0.2153 | 0.9123 |
| Std.Dev. | 24.410 | 0.1891 | 0.1156 | 0.1026 | 0.0402 |
| Coeff.Var. | 132.3% | 49.7% | 15.5% | 47.6% | 4.4% |

a) in the SB model, H0:β2=0 was rejected for three cultivars; b) in the MSB model, H0:β1=1 was rejected for four cultivars and H0:β2=0 for one; c) in the DBS model, H0:β1=1 was rejected for two cultivars, different from those in model MSB, H0:β2=0 was rejected for four cultivars and H0:β3=0 for one; d) in the FJ model, only H0:β2=0 was rejected for six cultivars and, e) in the QM model, H0:β1=1 was rejected for three cultivars and

**Table II** - Means (M), standard deviation (SD) and coefficient of variation (CV) obtained from the estimates of the parameters (β0, β1, β2, and β3) of the equations, of the deviations from regression mean squares (MSD) and of the determination coefficient ($R^2$) of 33 maize cultivars, by different methods.

| Methods | β0 | β1 | β2 | β3 | MSD | $R^2$ |
|---|---|---|---|---|---|---|
| *Silva and Barreto (SB) - Silva and Barreto (1985)* | | | | | | |
| M | 3.9771 | 1.0000 | 0.0000 | | 0.19974 | 0.9124 |
| SD | 0.3578 | 0.1331 | 0.2422 | | 0.08562 | 0.0351 |
| CV | 9.0% | 13.3% | --- | | 42.8% | 3.08% |
| *Modified Silva and Barreto (MSB) - Cruz et al. (1989)* | | | | | | |
| M | 3.9771 | 1.0000 | 0.0000 | | 0.20223 | 0.9113 |
| SD | 0.3270 | 0.0802 | 0.1515 | | 0.08431 | 0.0343 |
| CV | 8.2% | 8.0% | --- | | 41.7% | 3.7% |
| *Discontinuous Bi-Segmented (DBS) - Storck (1989)* | | | | | | |
| M | 3.977 | 1.0000 | 0.0000 | 0.0000 | 0.20596 | 0.9098 |
| SD | 0.396 | 0.1761 | 0.2525 | 0.2814 | 0.09095 | 0.0371 |
| CV | 9.9% | 17.6% | --- | --- | 44.2% | 4.1% |
| *Fonseca Junior (FJ) - Fonseca Jr. (1987)* | | | | | | |
| M | 3.9771 | 1.0000 | 1.0000 | | 0.19974 | 0.9124 |
| SD | 0.3578 | 0.1331 | 0.1544 | | 0.08562 | 0.0350 |
| CV | 9.0% | 13.3% | 15.4% | | 42.8% | 3.8% |
| *Quadratic regression (QM) - Brasil and Chaves (1988)* | | | | | | |
| M | 3.9771 | 1.0000 | 0.0000 | | 0.20055 | 0.9121 |
| SD | 0.3313 | 0.0779 | 0.0423 | | 0.08515 | 0.0348 |
| CV | 8.3% | 7.8% | --- | | 42.4% | 3.8% |

H0:β2=0 for five cultivars. The criteria of the significances of the tests of hypotheses did not provide enough information to choose a model for this set of data.

The mean estimates of the cultivar parameters (β0, β1, β2, and β3) do not differ among the linear models (Table II). However, the standard deviation (SD) of these estimates, the deviation from regression mean squares and the determination coefficients are different. Models with high SD for the parameter estimates facilitate the selection and screening of cultivars. The DBS model determination coefficients ($R^2$) and deviation from regression mean squares (MSD) were, on average, similar to those from the other models. However, they were more variable, implying a greater variation coefficient, which is an advantage of this model.

Among the linear models, only MSB and DBS showed the important property of independence between the estimates of the two segment angles, as the

**Table III** - Means (M) and standard deviation (SD) of the average quadratic deviations obtained for 33 cultivars for the models of Silva and Barreto (1985) (SB), modified SB (MSB), discontinuous bi-segmented (DBS), Fonseca Junior (1987) (FJ) and quadratic regression (QM) for different limits of environmental variability.

| Limits | SB | MSB | DBS | FJ | QM |
|---|---|---|---|---|---|
| *A - within the limits of the observed environmental indexes* | | | | | |
| M | 0.02426 | 0.02844 | 0.02876 | 0.02426 | 0.02178 |
| SD | 0.03363 | 0.03614 | 0.03428 | 0.03363 | 0.03049 |
| *B - from the lower limit to 0.7 K (assymtotic point)* | | | | | |
| M | 0.3658 | 2.9464 | 0.3167 | 0.3658 | 0.6729 |
| SD | 1.3018 | 12.043 | 1.1669 | 1.3018 | 2.5277 |
| *C - first half of limit B* | | | | | |
| M | 0.30840 | 0.34708 | 0.17040 | 0.30840 | 0.30543 |
| SD | 1.27320 | 1.34430 | 0.69187 | 1.27320 | 1.24530 |
| *D - second half of limit B* | | | | | |
| M | 0.06208 | 0.57096 | 0.05931 | 0.06208 | 0.00715 |
| SD | 0.25406 | 2.33020 | 0.24080 | 0.25406 | 0.03254 |
| *E - first third of limit B* | | | | | |
| M | 0.05198 | 0.26580 | 0.04649 | 0.51979 | 0.03554 |
| SD | 0.21604 | 1.06810 | 0.18259 | 0.21604 | 0.15262 |
| *F - second third of limit B* | | | | | |
| M | 0.02928 | 0.02053 | 0.01668 | 0.02928 | 0.02970 |
| SD | 0.11967 | 0.07575 | 0.06693 | 0.11967 | 0.12106 |
| *G - last third of limit B* | | | | | |
| M | 0.01335 | 0.10273 | 0.03898 | 0.01335 | 0.00223 |
| SD | 0.05459 | 0.44545 | 0.15555 | 0.05459 | 0.00853 |

covariance (β1; β1+β2)=0 (Cruz *et al.*, 1989; Storck, 1989). In the MSB model the hypothesis H0:β1=0 was rejected for four cultivars and in the DBS model for two different cultivars. The hypothesis H0:β2=0 was rejected only for one cultivar in the MSB model and in the DBS model for the same and three other cultivars. There was no consistency. However, the quality of the adjustments, estimated by the deviation from regression mean squares was, on average, the same. Consequently, these differences in significances are attributed to the reparametrization of the independent variables in the MSB model, which resulted in a value in the position [3.3] of the variance-covariance matrix of the estimates of the parameters (referring to the parameter β2=0.1802), 5½ times greater than the value in the position [2.2] (referring to the parameter β1=0.0326). In the MSB model the extrapolation of the first segment straight line has to pass through the mean of the second segment and this can cause a bias in the estimates of the first and/or second segment. Thus it is believed that these tests of hypotheses for the DBS model are superior because the relationship between the variances (position [3.3] = 0.36287 and [2.2] = 0.21527) was only 1 to 1.7. The esti- mates of β1 are more evenly distributed in the DBS model and this facilitates discrimination among the cultivars.

The comparison of each linear model with the adjusted NLM (standard) leads to better statistics to choose the best model. The statistic used, in this case, was the average quadratic deviation (AQD). The mean and the standard deviation of the AQD of the 33 cultivars, for the five linear models and for the different limits of the independent variable, are shown in Table III. When the environmental factors varied within the observed values (limit A - Table III), the models SB and FJ were identical in their quality of fit, being worse than the QM and better than the MSB and DBS models. The matrix of the AQD between model correlations, for the 33 cultivars, showed positive values superior to 0.94 for all the combinations among the models. Thus, any of the linear models assessed could efficiently substitute the NLM.

When wider environmental variations were applied (limit B - Table III), the AQDs were smaller and less well distributed for the DBS model. Thus, under more general conditions the DBS model adjusts better to the NLM. This generalization for comparason of models was not used by other authors (Carvalho *et al.*, 1983; Fonseca, 1987; Brasil and Chaves, 1988; Duarte and Zimmermann, 1992).

When the five linear models were fitted over the first and final halves of the curve of each cultivar (limits C and D - Table III), the DBS model also produced smaller and less evently distributed AQDs. All the models adjusted better to the final half of the curves.

When the range of the environmental variation of each cultivar was divided into three parts (first third, middle and final third) and the five linear models were fitted (limits E, F and G - Table III), the DBS model was better because it gave smaller and less evenly distributed AQDs. The fit of all the models to the middle third was better than to the initial third. This can be justified by the greater linearity of the values in this interval. The linear regression model of Eberhart and Russell (1966) is also suitable in this case.

The models were compared without corrections due to the errors of the dependent variable and their correlations with the dependent variable errors, because this was only available for the DBS model

(Storck, 1989). However, similar results in the comparisons should be obtained with the correction in all the models. The program for the calculations and tests of hypothesis, with and without the corrections for the DBS model is available from the author, in compiled form, to anyone who may be interested.

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## RESUMO

Uma análise de estabilidade fenotípica do rendimento de um grupo de 33 cultivares de milho, avaliados em 19 locais do Rio Grande do Sul, foi procedida pelo modelo não-linear, curva de crescimento de Gompertz. Foram ajustados cinco modelos lineares, visando compará- los entre si e estes com o modelo não-linear, tomado como padrão. Dos modelos lineares avaliados, quatro foram segmentados de diferentes formas e um contínuo, modelo de regressão quadrático. O modelo bi-segmentado descontínuo (Storck, Tese de Doutorado, ESALQ, USP, Piracicaba, SP, 1989) foi o melhor porque: apresenta a independência entre os ângulos dos dois segmentos; os testes de hipóteses para o segundo segmento é independente da descontinuidade; os valores estimados se ajustam bem a uma curva de crescimento de Gompertz; as estimativas dos parâmetros são mais dispersos; o modelo se ajusta melhor a situações mais amplas, isto é, sobre uma curva de crescimento completa, sobre a metade inicial e metade final da curva e sobre o terço inicial e médio da curva.

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