P L A N T B R E E D I N G A N D S E E D S C I E N C E
Volume 53 2006

Marcin Kozak

Department of Biometry Warsaw Agricultural University, Nowoursynowska 159, 02-776 Warsaw, Poland
e-mail: marcin.kozak@omega.sggw.waw.pl

TWO-DIMENSIONAL PARTITIONING OF YIELD VARIATION: A CRITICAL NOTE

ABSTRACT

The Two-Dimensional Partitioning (TDP) of Yield Variation is a method for studying a response variable (usually yield) as affected by successive traits contributing to it (first direction) and treatments (second direction). Many authors have found its usefulness, especially in plant breeding, but also in other agricultural and horticultural investigations. Since now, no disadvantages of the method have been pointed out. The objective of this paper is to discuss the statistical appropriateness of the TDP method. Two general problems are introduced, i.e., (1) employing sums of squares from ANOVA as factor effects, and (2) dealing with so-called cross-products, which cause that the TDP table is, actually, quite often very hard or even impossible to interpret. The author points out that inference based on TDP may be false and may lead to erroneous conclusions.

Key words: analysis of variance, Gram-Schmidt orthogonalization, sequential yield analysis, two-dimensional partitioning.

INTRODUCTION

The Two-Dimensional Partitioning of Yield Variation (abbr. TDP) is a statistical method proposed by Eaton *et al.* (1986) to provide an overall view of yield formation in terms of affecting yield by both treatments and yield components. It joins two basic and common statistical approaches to studying this process, namely multiple regression analysis, which deals with effect of plant and crop traits on yield, and analysis of variance, which deals with effect of treatments (controlled by an investigator) on yield. Moreover, the method applies a so-called ontogenetic approach to multiple regression, in which it is assumed that the traits develop in an ontogenetic order, which in turn results in a specific form of the cause-and-effect relationships between the components (Gołaszewski *et al.*, 1998). Such assumption brings about a specific approach to the regression analysis; it is, in fact, a specific forward regression in which the variables are added into the model in the ontogenetic sequence assumed (Mądry *et al.*, 2005). From the calculation point of view, the regression model is estimated for predictor variables under study transformed via the Gram-Schmidt ortogonalization (cf., e.g., Winer, 1971). From a bio-

Communicated by Andrzej Anioł

logical and physiological point of view, in many cases such an approach to plant development is commonly accepted (for concise but convincing discussion see, e.g., Dofing and Knight, 1992).

Eaton *et al.* (1986) developed TDP to assess determining yield by its multiplicative components and treatments. They used logarithmic transformation to obtain an additive model instead of the multiplicative one. In other analyses, in which investigated traits are not multiplicative components, the method also can be useful, but the logarithmic transformation should not be used. In the opinion of Gołaszewski (1996), even in yield component analysis this transformation can be omitted; instead of yield components, so-called primary characters (Sparnaaij and Bos, 1993), which are ratios of the primary characters (Sparnaaij and Bos, 1993; Gołaszewski, 1996; Kozak and Mądry, 2004), are then used.

TDP procedure aims at partitioning the total yield variation into increments of variation due to successive traits (first direction) and treatments (second direction) (Eaton *et al.*, 1986; Gołaszewski, 1996). This partitioning is done for both sums of squares from ANOVA and their percentage contribution to total yield sum of squares.

Many investigators have found the TDP method very useful in various plant breeding, horticultural and agronomical experiments (e.g., Gołaszewski *et al.* 1996, 1998; Spaner *et al.*, 2000, 2001; Bowen and Kliewer, 1990; or Shamaila *et al.*, 1992; etc.). Gołaszewski *et al.* (1996, 1998) claimed that TDP is useful in determining characters that are the most important in yield formation and hence should be considered in plant breeding programs. In the opinion of Gołaszewski *et al.* (1996), the statistical and interpretational simplicity and clarity of TDP makes the method very helpful in breeding (e.g., in plant breeding field trials with new cultivars; Gołaszewski *et al.*, 1998) and other agricultural investigations. Akwilin Tarimo (1997) used the TDP method to investigate a physiological response of groundnut to agronomic practices. He claimed that TDP was intensively applied, especially by plant breeders and plant physiologists, to identify traits useful for crop yield improvement; he found the usefulness of the method in understanding plant allometric relationships under different cultural practices. Finally, the main advantage of TDP lies in its condensation (Eaton *et al.*, 1986).

Although so many good opinions on the TDP method have been given, several questions regarding its correctness arise and make the usefulness of the method disputable. Since now, no drawbacks of the method have been provided in the literature. The objective of this paper is to criticize the statistical appropriateness and interpretational utility of the Two-Dimensional Partitioning of Yield Variation.

TDP METHOD

Statistical basis of the method was described in several papers, see, e.g., Eaton *et al.* (1986), Gołaszewski (1996), or Gołaszewski *et al.* (1998). Probably the most thorough description is given by Gołaszewski (1996); hence, we shall introduce just a general but not detailed description of the method. For details, see the papers mentioned.

The biological sequence of the investigated traits has to be assumed at the outset. If there is no unequivocal evidence that the traits develop sequentially, the TDP method should not be used.

Consider the set of variables ($\mathbf{X}^T$, Y), where $\mathbf{X}=(X_1,\ldots,X_p)^T$ is the set of k predictor variables (in their assumed sequence in the plant ontogenesis) and Y is the response variable, i.e., yield (usually). Consider an n-element sample $(\mathbf{X}_i^T, Y_i)^T$, $i=1,\ldots,n$, originating from a factorial experiment. Provided that the classical assumptions of multiple linear regression analysis and analysis of variance (cf., e.g., Quinn and Keough, 2003, sec. 6.1.7 and 9.2.8) are fulfilled, the multiple linear regression analysis for the model $E(Y|\mathbf{X}^T)$ and the $p+1$ analyses of variance can be evaluated for the sample data.

Calculations in the TDP procedure can be presented in the following general steps (e.g., Eaton *et al.*, 1986; Gołaszewski, 1996; Gołaszewski *et al.*, 1996):

(1) Transform the original traits $X_1,\ldots,X_p$ via the Gram-Schmidt orthogonalization (Winer, 1971), to obtain $p+1$ orthogonal (stochastically independent) variables Z_i, $i=1,\ldots,p+1$; (the last orthogonal variable, Z_{p+1}, is the residual variable from the model $E(Y|\mathbf{X}^T)$). Let $\mathbf{Z}=(Z_1,\ldots,Z_{p+1})^T$.

(2) Estimate the linear regression model $E(Y|\mathbf{Z}^T)$.

(3) Scale the variables Z_i, $i=1,\ldots,p+1$, i.e., multiply their sample values by the corresponding partial regression coefficient obtained in step 2.

(4) Conduct $p+2$ analyses of variance, (appropriate for the design of the experiment,) for all scaled orthogonal variables and yield.

(5) On the basis of the results of the regression and ANOVA analyses, construct two two-dimensional tables, first one based on sums of squares from ANOVA, and second one on proportions (in per cents) of these sums of squares in total yield sum of squares.

(6) Statistical significance in the last row of the table originates from the regression analysis, and in other cells of the table (besides residual row, obviously) from ANOVAs.

The tables constructed in steps 5 and 6 provide information on affecting yield by both directions, i.e., by contributing successive traits and by treatments and error. (Usually, only the second table is taken into account in the interpretation.)

The TDP method has been intensively used in horticulture investigations (e.g., McArthur and Eaton, 1988; Freeman *et al.*, 1989; Bowen and Kliewer, 1990; Shamaila *et al.*, 1992), plant breeding (e.g., Gołaszewski *et al.*, 1996, 1998, 2001), and other agricultural experiments (Gołaszewski *et al.* 2000; Spaner *et al.*, 1996, 2000, 2001).

DISCUSSION ON TDP

Two main problems regarding appropriateness of the TDP method arise. Let us examine them in detail.

Employing of sums of squares

In TDP, sums of squares (SSs) from ANOVA are used to assess the contribution of each cell (source of variation × orthogonal variable) to the total yield variation.

This is a very disputable approach, since sums of squares from ANOVA may not be used as comparable coefficients of treatments contribution to variation in the dependent variable (so-called factor effects; Quinn and Keough, 2003, p. 188). In a case of random effects, variance components may be considered as such factor effects. Unfortunately, in a case of fixed factors this is not the case. Several forms of the factor effects, so-called proportion of explained variance PEV (Quinn and Keough, 2003, p. 190), in the case of fixed models were proposed; e.g., ω^2 (Hays, 1994) or Cohen's effect size *f* (Cohen, 1998). Quinn and Keough (2003, p. 191) propose to use the mean squares from ANOVA. They are useful for a particular analysis, but still are incomparable between different analyses (Quinn and Keough, 2003, p. 191).

Returning to the sums of squares, they are incomparable between both different sources of variation and different ANOVAs. It is mainly because of different degrees of freedom on which they are based. Unfortunately, SSs are sometimes used as a factor effects measure (besides the papers with TDP, see, e.g., Panayotova and Valkova, 2003), but such an approach is incorrect from a statistical point of view.

Occurrence of cross-products

In the TDP method, so-called cross-products for each source of variation occur in the TDP tables (they are usually denoted XX_d, where *d* corresponds to a *d*th source of variation). Sometimes they are not explained (e.g., Akwilin Tarimo, 1997), sometimes treated as compensation (product terms) (Shamaila *et al.*, 1992; Spaner *et al.*, 2000, 2001), or as the possible interaction between components (Gołaszewski *et al.*, 2001). The fathers of the method, Eaton *et al.* (1986), provided that cross-products are an embracement of all possible interactions between treatments and component pairs. The same explanation gave Gołaszewski *et al.* (1998). It means that treatments may have opposing effects upon components of a pair, which both contribute in the same (positive or negative) direction to yield (Eaton *et al.*, 1986).

In what follows, ignoring cross-products effect on interpretation is disputed. Unfortunately, it is a common procedure: To infer from TDP without considering cross-products, even in spite of their large values.

May occurrence of cross-products cause any problems in interpretation? First, let us go through some of their properties. Their sum is equal to zero (as well as the sum of all SSs from the TDP table). Certainly, column values (SSs or percents) for the sources of variation sum up to the corresponding total (SSs or 100%) from the last row; it is known from ANOVA. But the SSs related to a particular treatment for orthogonal variables (, where A is the treatment, k=1,...,p+1) do not sum up to the SS for this treatment and yield (SS_Y). The cross-product XX_A for a treatment A is equal to:

$$XX_A = SS_Y - \sum_{k=1}^{p+1} SS_{Z_k}$$

How are we to interpret a cross-product? Let us look at some examples from the literature.

Eaton *et al.* (1986), the fathers of TDP, presented the method for cucumber yield components (all variables were considered in log scale): stem length/plant, leaf area/leaf, fruits/leaf area, and weight/fruit. The experiment consisted of only oxy-

gen treatment (hence, there were two sources of variation, namely the treatment and error). Yield was significantly affected by the oxygen treatment and by fourth and fifth component. Only fourth component, fruits/leaf area, was affected by the treatment, unlike the other ones. The cross-products for the treatment and error were negligible (–0.002 and 0.002%, respectively), hence, in fact, they did not affect the interpretation.

However, how could we interpret a situation in which cross-products values are large? It is possible to obtain much larger cross-products for one or more treatments than the corresponding sums of squares for yield, i.e., $XX_A > SS_{Y,A}$ (when treatment A is taken into account). Such a situation can occur especially in multifactor experiments. For instance, in an investigation on quality attributes of some strawberry cultivars, Shamaila *et al.* (1992) studied affecting overall fruit quality by several independent variables (quality attributes) and factors: year (Y), cultivar (C), judge (J), replicate (R), and factors interactions. $SS_{Y,C}$ (i.e., sum of squares for overall quality attributes as the response variable, and cultivars as a source of variation) was 1.1, whereas the corresponding cross-products was XX_C=18.6. This is the very large difference; it resulted from the large SS for the residual variable. Actually, this problem disturbs one of the directions of the interpretation, the one related to treatments and their influence on the dependent and orthogonal independent variables.

In an investigation by Spaner *et al.* (2000) on winter wheat yield studied as affected by yield components, for one of cross-products the authors obtained a percentage value 43%! This lack of 43% in one row is probably not possible to interpret. In almost all multifactor investigations, cross-products occur and there is no way to forget them when interpreting the results.

concluding remarks

The objective of the TDP method is to partition the yield variation into two directions, one due to treatments and second due to traits. A method enabling this would be very useful in many plant breeding, physiological, agronomical, and other agricultural investigations. Unfortunately, it was proofed in this paper that the TDP method has two drawbacks that make it provide false interpretation; those drawbacks are employing of sums of squares from ANOVA and occurring of cross-products. Even if cross-products values are negligible, use of sums of squares as factor effects cause that the TDP method should not be used because of erroneous interpretation and conclusions. In fact, the two described problems are related because, as it was mentioned, the ANOVA's sums of squares are not comparable between different studies; in fact, this is performed on the basis of a TDP table: comparing the SSs for different variables. They are also incomparable for a particular study (i.e., for treatments); it is also done in TDP.

REFERENCES

Akwilin Tarimo, J. P. (1997). Physiological Response of Groundnut to Plant Population Density. Afr. Crop Sci. J. 5, 267-272.

Bowen P.A., Kliewer W.M. 1990. Influence of Clonal Variation, Pruning Severity, and Cane Structure on Yield Component Development in 'Cabernet Sauvignon' Grapevines. J. Amer. Soc. Horticult. Sci. 115, 530-534.

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences. 2nd Edition. Lawrence Erlbaum, Hillsdale, New York.
Dofing, S. M., Knight, C. W. (1992). Alternative Model for Path Analysis of Small-Grain Yield. Crop Sci. 32, 487-489.
Eaton, G.W., Bowen, P.A., Jolliffe, P.A. 1986. Two-dimensional Partitioning of Yield Variation. HortScience 21, 1052-1053.
Freeman J.A., Eaton G.W., Baumann T.E., Daubeny H.A., Dale A. 1989. Primocane Removal Enhances Yield Components of Raspberries. J. Amer. Soc. Horticult. Sci., 114, 6-9.
Gołaszewski, J. (1996). A Method of Yield Component Analysis. Biometrical Letters 33(2), 79-88.
Gołaszewski, J., Idźkowska, M., Milewska, J. (1998). The TDP Method of Seed Yield Component Analysis in Grain Legume Breeding. J. Appl. Genet. 39(4), 299-308.
Gołaszewski, J., Idźkowska, M., Milewska, J., Koczowska, I. (2001). Yield Component Analysis with SYCA and TDP in Fodder Pea. Plant Breed. Seed Sci. 45(2), 77-85.
Gołaszewski, J., Idźkowska, M., Milewska, J., Koczowska, I., Kosiorek, A. (2000). Yield Component Analysis in Agricultural Studies. Fragmenta Agronomica 4, 15-27 (in Polish).
Gołaszewski, J., Milewska, J., Koczowska, I. (1996). Two-dimensional Partitioning in Yield Variation of Field Bean (Vicia Faba L.) Strains. Acta Acad. Agricult. Tech. Olst. 63, 147-153 (in Polish).
Hays, W. L. (1994). Statistics. 5th Edition. Harcourt Brace, Fort Worth.
Kozak, M., Mądry, W. (2004). Statistical Analysis of Multiplicative Crop Yield Components – Background of Yield Modeling. Post. Nauk Roln. 5, 13-25 (in Polish).
Mądry, W., Kozak, M., Pluta, S., Żurawicz, E. (2005). A New Approach to Sequential Yield Component Analysis (SYCA): Application to Fruit Yield in Blackcurrant (Ribes nigrum L.). J. New Seeds 7(1), 85-107 (in press).
McArthur D.A.J, Eaton G.W. (1988). Strawberry Yield Response to Fertilizer, Paclobutrazol and Chlormequat. Scientia Horticulturae 34, 33-45.
Morrison, D. F. (1983). Applied Linear Statistical Methods. Englewood Ciffs, NJ: Prentice-Hall.
Panayotova, G., Valkova, N. (2003). Stability of Cotton Yield Influenced by Nitrogen Fertilization and Irridation with Gramma-Rays. Bulg. J. Agric. Sci. 9(1), 17-22.
Quinn, G. P., Keough, M. J. (2003). Experimental Design and Data Analysis for Biologists. Cambridge University Press, Cambridge.
Shamaila, M., Baumann, T. E., Eaton, G. W., Powrie, W. D., Skura, B. J. (1992). Quality Attributes of Strawberry Cultivars Grown in British Columbia. J. Food Sci. 57(3), 696-699.
Spaner D., Mather D.E., Brathwaite R.A.I. (1996). Yield and quality attributes of rainfed green corn in Trinidad. HortTechnology 6, 131-134.
Spaner, D., Todd, A. G., McKenzie, D. B. (2000). The Effect of Seeding Date, Seeding Rate and N Fertilization on Winter Wheat Yield and Yield Components in Eastern Newfounland. Can. J. Plant Sci. 80, 703-711.
Spaner, D., Todd, A. G., McKenzie, D. B. (2001). The Effect of Seeding Rate and Nitrogen Fertilization on Barley Yield and Yield Components in a Cool Maritime Climate. J. Agron. & Crop Sci. 187, 105-110.
Sparnaaij, L.D., Bos, I. (1993). Component Analysis of Complex Characters in Plant Breeding. I. Proposed Method for Quantifying the Relative Contribution of Individual Components to Variation of the Complex Character. Euphytica 70, 225-235.
Winer, B. J. (1971). Statistical Principles in Experimental Design. 2nd ed. McGraw-Hill, New York, 126-133.