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A GRAPHICAL ASSESSMENT OF DATA FROM INTERCROPPING FACTORIAL EXPERIMENTS†

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SUMMARY

A graphical method, based on bivariate analysis, is used to present yield data from intercropping experiments involving two crop species. The method is used to demonstrate two- and three-factor interactions in factorial experiments.

The importance of intercropping in farming systems is widely recognized throughout the tropical areas of the world (Francis *et al.*, 1977; Okigbo and Greenland, 1977) and in recent years research on intercropping systems has expanded greatly (Willey, 1979). In contrast, most statistical techniques have been developed largely for studies of sole cropping and until recently few techniques have been available for intercropping (Mead and Riley, 1981). Major problems in presenting the results from intercropping experiments are how to include data (e.g. yield or quality) on the various species that constitute the mixture, and how to assess the effects of different treatments on those species?

One approach has been to convert the data to a common measure, the simplest being the total agronomic yield of the mixture. More complex measures are those that include a direct comparison with sole crop yields, e.g. Relative Yield Totals (De Wit, 1960) and Land Equivalent Ratios (Anon, 1972), and then to use techniques previously developed for dealing with a single variate. All techniques that rely on converting data to a single variate suffer disadvantages. First, the single derived variate may have little practical value (e.g. overall agronomic yield, when the economic or food value of the components differ markedly), or may be valid only under certain conditions (e.g. net profit). Secondly, conversion to a single variate results in a loss of information, most commonly on crop proportions in the mixture.

In view of the disadvantages of converting to a single variate it seems worth while to devote more attention to reintroducing the methods of analysing multivariate data such as those derived from intercropping experiments. Pearce and Gilliver (1978) considered the case of mixtures including two crops and devised a bivariate method for analysing their results. In a subsequent paper (1979), they extended the graphical methods for presenting the data. Their

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approach takes into account the correlation between the original variates of the two species and allows a transformation to give new variates that are independent.

This paper presents the results of an intercropping experiment with two species and factorial structure, analysed using the techniques developed previously. Methods of interpreting the main effects and interactions are illustrated using a graphical technique.

METHODS AND RESULTS

Bivariate method

Let the variates from the two species be X_1 and X_2, with error variance V_{11} and V_{22} and error covariance V_{12}. Also let V'_{11} and V'_{22} be the variances, after adjusting each variate by the other, i.e.

$$V'_{11} = V_{11} - V_{12}^2/V_{22} \quad \text{and} \quad V'_{22} = V_{22} - V_{12}^2/V_{11}.$$

Two new independent variates, Y_1 and Y_2, can be formed by

$$Y_1 = X_1/\sqrt{V_{11}} \quad \text{and} \quad Y_2 = (X_2 - V_{12}X_1/V_{11})/\sqrt{V'_{22}}.$$

Hence, Y_2 derives from X_2 after allowing for the effect of X_1. Since Y_1 and Y_2 are independent, they can be graphed in the usual way. The method is illustrated in Fig. 1.

The point P is reached by going $X_1/\sqrt{V_{11}}$ along the Y_1 axis to N and then

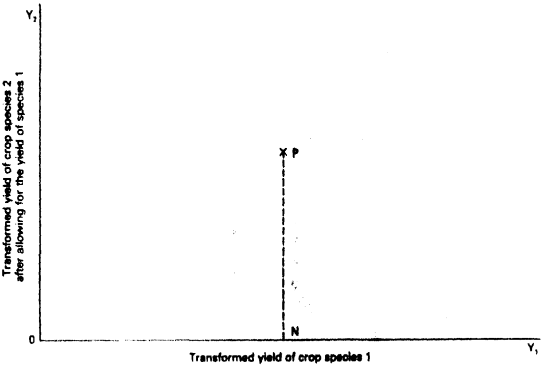

Fig. 1. A way of representing the result of a treatment in a two-species intercropping experiment. Y_1 and Y_2 represent derived variates for purposes of statistical analysis.

vertically $(X_2 - V_{12}X_1/V_{11})/\sqrt{V'_{22}}$ parallel to the Y_2 axis. It is assumed that the correlation coefficient will not depend upon the treatment. Values formed from the transformed independent variates can be analysed and the significance judged using the bivariate F-values. As with the univariate case, main effects and interactions can be assessed.

Graphical representation of an interaction

It is convenient to consider first the case where there is only a single species, i.e. the *univariate* case. Taking the simplest example, let there be two factors A and B each at two levels (1 and 2), i.e. the familiar 2^2 factorial design, with the four treatments giving mean values of A_1B_1, A_1B_2, A_2B_1 and A_2B_2, respectively. If A and B operate independently of one another:

$$A_2B_2 = A_1B_1 + (A_2B_1 - A_1B_1) + (A_1B_2 - A_1B_1) = A_2B_1 + A_1B_2 - A_1B_1$$

The extent to which the actual value of A_2B_2 differs from the expected value is called the *interaction* of A and B, usually written $A \times B$.

This situation is expressed graphically in Fig. 2. The means can be placed on a line, though it is often helpful to follow the practice suggested by Cox (1959) of displacing points that involve one of the modifications. If there is no interaction the result is two parallel lines (Fig. 2a), but if there is an interaction the lines are not parallel (Fig. 2b).

When there are two species, i.e. the *bivariate* case, the diagram requires at

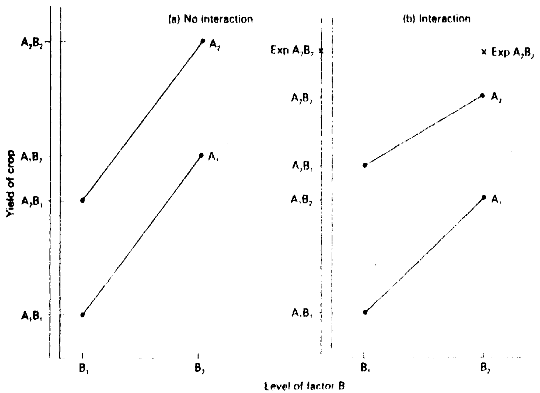

Fig. 2. Illustration, in one and two dimensions, of (a) no interaction and (b) interaction of two factors A and B each with two levels.

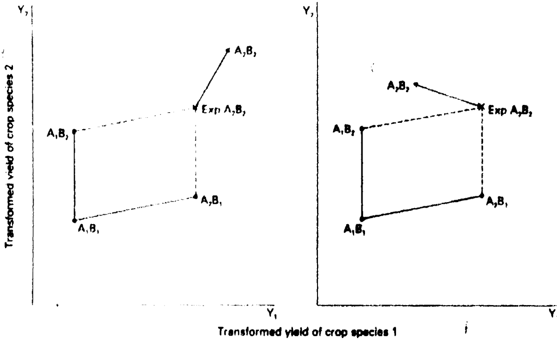

Fig. 3. Two-factor interactions of the same magnitude but with different agronomic implications.

least two dimensions and the results can be plotted as in Fig. 1. Points A_1B_1, A_2B_1, A_1B_2 and A_2B_2 in Fig. 3 show the results from the four treatments. If B has the same effect in the presence and absence of A, the expected point A_2B_2 completes the parallelogram defined by the points A_1B_1, A_2B_1 and A_1B_2. If the actual point lies elsewhere, its displacement represents the interaction. The displacement of the observed point A_2B_2 from the expected value is shown in Fig. 3 by a solid line capped with an arrow. A circle drawn round the expected point A_2B_2 will give the same significance level for the interaction. However, the practical interpretation will depend on the actual location of A_2B_2 (e.g. in the two cases shown in Fig. 3 the interactions are equal in magnitude, and therefore in statistical significance, but very different in their agronomic implications).

The bivariate interaction combines both the univariate interactions for the two variates, Y_1 and Y_2, i.e. (Bivariate interaction)^2 = (Univariate interaction for Y_1)^2 + (Univariate interaction for Y_2)^2, since Y_1 and Y_2 are independent and the rules of geometry apply. A bivariate test will normally be more sensitive to treatment effects than either univariate test.

If there are three factors the situation is complicated only slightly, as Fig. 4 shows. If the points for treatments $A_1B_1C_1$, $A_2B_1C_1$ and $A_1B_2C_1$ are plotted they give the expected point for $A_2B_2C_1$. The displacement of the actual point from its expected position shows the interaction, $A \times B$, in the absence of C. If the points $A_1B_1C_2$, $A_2B_1C_2$ and $A_1B_2C_2$ are now plotted, completing the parallelogram, and adding the interaction just found for $A \times B$ in the absence of C, will give an expected point for $A_2B_2C_2$. The displacement of the actual point from its expected position will give the three-factor interaction, $A \times B \times C$.

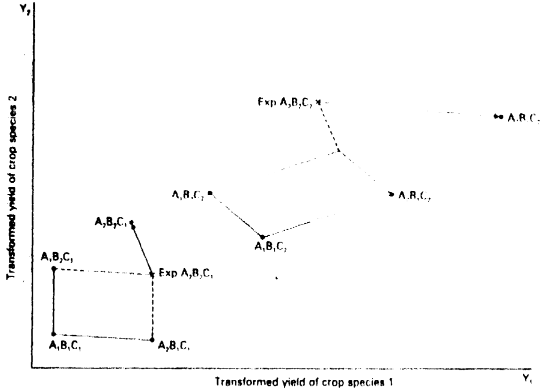

Fig. 4. Graphical representation of data from a three-factor experiment illustrating three-factor interaction.

Again, all points at a given distance from the expected position will be the same as far as significance levels are concerned, though they might well lead to different practical conclusions. The fact that the two parallelograms in Fig. 4 have different shapes is irrelevant to the estimation of the three-factor interaction, though it may well indicate two factor interactions such as $A \times C$ or $B \times C$. The order of the factors is immaterial; the interactions $A \times B \times C$, $B \times A \times C$, $B \times C \times A$ are the same. Here too the bivariate interaction can be derived from the univariate.

Further extension to a larger number of factors is straightforward. Sometimes factors will have more than two levels, as when several varieties or fertilizer regimes are compared. This situation is more difficult to represent unless it is possible to break down the contrasts into single degree of freedom effects (e.g. three equally-spaced fertilizer applications can be presented as a linear and a quadratic effect).

Numerical examples

The results used here are from two experiments, each with eight treatments in four blocks, carried out on an alfisol (red soil) at ICRISAT, which is located 25 km north west of Hyderabad, India, at 17.5° N and an altitude of 545 m. The two experiments involved intercropping of pigeonpea (*Cajanus cajan*) with pearl millet (*Pennisetum typhoides*) in 1977 and with sorghum (*Sorghum bicolor*) in 1978. Three factors (variety, fertilizer and planting method), each at two levels, were combined in a 2 x 2 x 2 factorial structure to give a total of eight treatment combinations. For each factor, Level 1 represented current local farming practice and Level 2 an improvement suggested by the extension service. Thus, V_1 was a local variety and V_2 a new introduction. The two fertilizer treatments were F_1, an application of farmyard manure at 10 t ha^{-1} and F_2, supplying ammonium sulphate (0.4 t ha^{-1}) plus a basal dressing of di-ammonium phosphate (75 kg ha^{-1}). The planting method was either flat planting (M_1) or on raised beds (M_2) each 1.5 m wide and 0.2 m high. The cereal: pigeonpea ratio on the raised beds was 2:1 in both years, while the ratio on the flat was 12:3 in 1977 and 6:2 in 1978. These ratios have a bearing on the interpretation of the results.

Only grain yield is considered here since the objective is to give an example of data interpretation using the bivariate method.

1978 Experiment

Taking X_1 as the grain yield of sorghum and X_2 as the corresponding pigeonpea yield, there was a positive correlation ($\phi = 66°$) between the two species. The mean yields of the actual values (X_1 and X_2) and the transformed variates (Y_1 and Y_2), taking account of the correlation between species, are presented in Table 1.

The bivariate analysis (Pearce and Gilliver, 1978) did not suggest a three-factor interaction and attention therefore passed to the significant two-factor interaction, namely $F \times V$ ($P < 0.001$), shown in Fig. 5b. The yield of sorghum was in fact greater for F_2V_2 than could be expected in the absence of an interaction. Furthermore, although there was a small decrease in Y_2, that variate included an allowance for the change in yield of sorghum. This decrease shows only that the yield of pigeonpea did not increase as much as might be expected bearing in mind the increase in yield of sorghum, the two being correlated positively. If the pigeonpea crop had been unaltered in absolute value, the line joining the expected and actual points for F_2V_2 would have been inclined to the

Table 1. *Mean grain yields (kg plot^{-1}) of sorghum (X_1) and pigeonpea (X_2) and the derived variates Y_1 and Y_2 for the 1978 experiment*

Treatment†	X_1	X_2	Y_1	Y_2
$V_1M_1F_1$	3.6	8.3	0.86	4.26
$V_1M_2F_1$	5.3	11.0	1.24	5.59
$V_1M_1F_2$	9.4	5.0	2.21	1.80
$V_1M_2F_2$	12.0	9.7	2.83	4.12
$V_2M_1F_1$	13.8	7.6	3.26	2.76
$V_2M_2F_1$	18.7	11.8	4.40	4.59
$V_2M_1F_2$	35.6	5.1	8.39	−0.98
$V_2M_2F_2$	41.1	12.1	9.67	2.34

† V_1 = local variety; V_2 = introduced variety; M_1 = planting on the flat; M_2 = planting on raised beds; F_1 = farmyard manure (10 t ha^{-1}); F_2 = ammonium sulphate (0.4 t ha^{-1}) plus a basal dressing of di-ammonium phosphate (75 kg ha^{-1}).

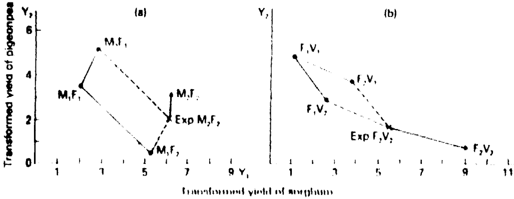

Fig. 5. The $M \times F$ (a) and $F \times V$ (b) two-factor interactions for 1978 data.

vertical at an angle ϕ (i.e. 66°) whereas it is much nearer to the horizontal. It thus appears that the two improvements on current practice represented by V_2 and F_2 are more effective when used together than might be expected from the use of either improvement alone. Then again, when these improvements are adopted in combination, both species gain.

Figure 5a sets out the non-significant interaction, $M \times F$. Since the factors F and M appear to act independently, the effect of M may be found by joining the mid-point of M_1F_1 and M_1F_2 to that of M_2F_1 and M_2F_2. The displacement is in fact significant ($P < 0.001$). It should be recognized that the sorghum:pigeonpea ratio was greater in flat plantings than on raised beds, which may account in part for the results observed. Although it is possible to deal with factor M in this way (because it does not enter into interactions) factor F, in contrast, interacts with varieties and it is not possible to generalize about it, though Fig. 5b sets out the position clearly.

1977 Experiment

The data for 1977 are used here to illustrate the three-factor interaction. Once again the grain yields of the two species were correlated positively (ϕ = 86°). The treatment means, transformed on account of this correlation, are presented in Table 2. As in the 1978 experiment, the treatments involving fertilizer, variety and planting method all had a significant effect ($P < 0.001$) on grain yield, but there was no significant fertilizer and variety interaction. Unlike the 1978 experiment, there were significant interactions of fertilizer and planting method ($P < 0.001$), variety and planting method ($P < 0.05$) and between the three factors ($P < 0.001$).

The significant three-factor interaction is rather more difficult to interpret. At each management level the parallelogram for the two factors is completed, as described previously, to obtain the expected value in the absence of an interaction. The displacement of the observed point for $M_1V_2F_2$ from the expected value is shown again by a solid line capped with an arrow. By adding this interaction to the other management level the three-factor interaction can be drawn and is shown by joining the points expected $V_2F_2M_2$ to actual $V_2F_2M_2$. The

Table 2. Mean grain yields (kg plot^{-1}) of pearl millet (X_1) and pigeonpea (X_2) and the corresponding derived variates Y_1 and Y_2 for the 1977 experiment

Treatment†	X_1	X_2	Y_1	Y_2
$V_1M_1F_1$	32.6	19.8	8.85	1.28
$V_1M_2F_1$	24.6	35.3	6.67	3.15
$V_1M_1F_2$	51.1	23.4	13.86	1.19
$V_1M_2F_2$	56.0	43.2	15.18	3.19
$V_2M_1F_1$	50.0	32.6	13.54	2.21
$V_2M_2F_1$	31.3	35.6	8.47	3.01
$V_2M_1F_2$	52.5	19.6	14.23	0.75
$V_2M_2F_2$	83.9	69.5	22.74	5.29

† As in Table 1 except for cereal species.

positive interaction between the three factors is apparent in Fig. 6 by the large displacement of the actual value of $V_2F_2M_2$ from the expected value. The grain yields of both pearl millet and pigeonpea are greatly increased when all three improvements are used together.

CONCLUSION

The graphical method described here for displaying interactions from a factorial experiment for a two-crop species intercropping situation depends on transforming the original data to new variates which are independent of one another. The method assumes a constant correlation between the species over all treatments, which has yet to be proven.

In general, graphical procedures have the benefit of displaying relations between variables which may not be obvious from tabulated data. The graphical procedure described here enables an interpretation to be made of the means

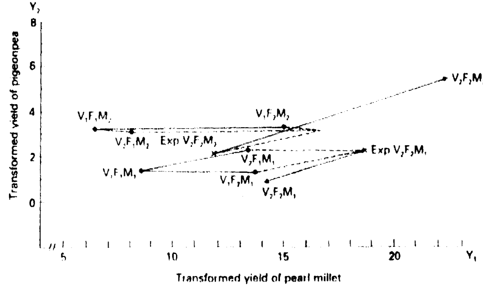

Fig. 6. Illustration of the three-factor interaction $V \times F \times M$ for 1977 data.

from a two-species intercrop factorial experiment. The size of interactions between factors, and their levels of significance if required, can be shown.

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