THE BIOMETRICAL ANALYSES OF INTERCROPPING EXPERIMENTS : SOME PRACTICAL ASPECTS WITH THE REFERENCE TO INDONESIAN INTERCROPPING EXPERIMENTS

A thesis submitted by

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TABLE OF CONTENTS

PAGE

LIST OF TABLES

LIST OF FIGURES

Figure Number	Title

SUMMARY

Most statistical analyses and designs developed for agricultural research are primarily meant for sole crop experiments. In intercropping experiments, however, the development of both designs and analyses is relatively primitive. In this thesis several biometrical techniques for intercropping are investigated. The suitability of these techniques is illustrated by analysing data from 51 Indonesian intercropping experiments.

The biometrical techniques used here have been applied to investigate three important aspects of intercropping experiments. The first aim is to assess the validity of the assumptions underlying the models and also to develop the previous models in order to assess yield advantages in intercropping. The second is evaluation of the cropping systems × environmental interactions and yield stability for intercropping. The third is a discussion of the role of competition analysis in intercropping experiments. The thesis also provides guidance on experimental designs for Indonesian intercropping experiments.

The assumption underlying two popular models in intercropping the Land Equivalent Ratio (LER) (Mead and Willey, 1980) and bivariate analyses (Pearce and Gilliver, 1978, 1979) are examined in Section IV.1. The LER is quite satisfactory as regards distribution and homoscedasticity as long as there are no outliers in the data. It is shown that for many data sets and analyses, the hypothesis of equality of correlation needs to be tested as well as that of equality of treatment means in the bivariate analysis of variance. Since there are two characteristics of interest (the two separate crop yields), then without knowing the criterion of "the best", the problems of choosing the best treatment will not be solved. Univariate and multivariate analyses are investigated in order to determine how best to assess the degree of yield advantage for intercropping systems (Section IV.2). The study emphasizes that more than one

analysis should be done in order to get a better understanding of the nature of any yield advantages. The joint use of LERs and bivariate analysis is suggested as the two methods complement each other. In order to have a comprehensive result, the study offers an alternative criterion of the best treatment, a new effective LER (LER'). The best treatment is defined as that which has the yield of the main crop meeting the farmer's requirements and which also has the highest biological efficiency in terms of LER'.

In view of the problems encountered in assessing both the interaction of cropping systems and environments and also yield stability in intercropping systems, the study treats these aspects extensively (Chapter V). On analysing the Indonesian intercropping data, one concludes that the experimenters seem not to realize the importance of these factors for intercropping systems, as few relevant experiments have been conducted. Accordingly, any conclusions must be tentative in the extreme, but the results have the merit of merging the study of cropping systems or cropping combination × environmental interaction for Indonesian intercropping experiments.

The usefulness of the bivariate graphical method (Pearce and Gilliver, 1978, 1979) is highlighted in Chapter VI in examining the nature of competition analysis for intercropping experiments. The study develops this technique and emphasizes that without distinguishing the degree of yield advantage, most published competition functions are largely uninformative. It is proposed that in order to have a better understanding of the final yields, one must consider growth and other characters of crops under intercropping.

Experimental design considerations and guidelines in designing Indonesian intercropping experiments are discussed in Chapter VII. The study shows that the experimenters in some cases have been confused about the objectives of experiments and consequently about relevant experimental designs. Much closer collaboration is needed between experimenters and statisticians; the lack of statisticians or biometricians in Indonesia may cause major problems in applying even the existing statistical methods for intercropping experiments. This has important implications for agricultural practice in developing countries.

DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of author's knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Waego H. Nugroho

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I. GENERAL INTRODUCTION

Intercropping or growing crops in mixtures is one of the important features of farming in developing countries (Jodha, 1979). It has long been recognized as a very common practice throughout the developing tropics and subtropics (Hardwood and Price, 1976; Willey, 1979). In India, its importance has been highlighted in a very comprehensive review by Aiyer (1949). Historically, however, as Andrew (1972) and Freyman and Venkanteswarlu (1977) mentioned, it has been regarded as a primitive practice among subsistance farmers which would give way to sole cropping as a natural and inevitable consequence of agricultural development. More recently, it has been realized that intercropping remains an extremely widespread practice and is likely to continue so for the forseeable future (Francis et al. 1975; Okigbo and Greenland, 1975).

There are some different definitions of intercropping or mixed cropping, but most writers agree that intercropping is the growing of two or more crops simultaneously on the same area of ground (Crookston, 1976; Pearce and Gilliver 1979; De and Singh, 1979 and Willey, 1979). The crops can be in alternating rows or mixed together within rows and also they are not necessarily sown at exactly the same time and their harvest time may be quite different, but they are usually simultaneous for a significant part of their growing periods. The two terms intercropping and mixed cropping have often been used synonymously in the past.

The main objective behind most intercropping experiments has been to investigate the output of the intercrops compared with the relevant monocrops and also to compare between intercrops themselves (Pearce and Gilliver, 1978; Mead and Willey, 1980). The other major reason for studying intercrops is that large areas of the tropics and subtropics have a growing season that is too long to be effectively utilised by a single crop, but too short for successful double cropping, i.e. one crop succeeding another in time (Andrew, 1972; Freyman and Venkanteswarlu, 1977). Mixed cropping has given higher returns per hectare than double or single cropping. As Fisher (1977) said, the yield advantage that would justify intercropping has commonly been thought to be a higher yield from the mixture than from an equal area divided between monocultures of the components in the same proportion as that in which they occur in the intercrop. Numerous reports of this kind of intercropping advantage (reviewed in Jensen (1952) and Simmonds (1962)) gave the impression that intercropping was highly desirable. More recently the advantage required to justify intercropping has been realised to be a superiority of the yield of the mixture over that of the better (or best) of its components grown in monoculture over the whole of the same area. Willey (1979); Gomez and Gomez (1983) also emphasized that intercropping increases the yield stability even during the bad years, there is still high enough yield to satisfy the minimum food requirement of the family. This is thought to be of particular importance to poorer subsistance farmers.

A major cause of yield advantages in growing crops together is that two or more crops with diverse growth habits or duration of growth, or both, may be able to exploit plant nutrients and moisture in different soil layers and intercept light more effectively than a single crop (Donald, 1963; and Trenbath, 1974, 1978). Other causes have been suggested (Willey, 1979), perhaps the most important of which is the possibility of better control of weeds, pests or diseases. The weed aspect is relatively straightforward, better control being possible where intercropping provides a more competitive community of crop plants either in space or time than sole cropping (Litsinger and Moody, 1975; Rao and Shetty, 1977). The pest and disease aspects are much more complex. Many instances of better control have been quoted (Aiyer, 1949; IRRI, 1973, 1975) and some of the possible mechanisms have been reviewed (Trenbath, 1974; Litsinger and Moody, 1975). However, there have also been instances of poorer control (Osiru and Willey, 1972; Pinchinat _et al._, 1975). Other possible causes of yield advantages may be important in certain situations but have as yet received little research attention, e.g. one crop may provide physical support for another (Aiyer, 1949), one may provide shelter for another (Radke and Hegstrom, 1975) or a more continuous leaf cover may give better protection against erosion (Seddoway and Bonnett, 1975).

However, it must be also appreciated that there can be some disadvantages of intercropping (Willey, 1979). These can take the form of a yield decrease because of adverse competitive effects, although such effects are likely to be rare. As Risser (1969) and Rice (1974) mentioned, allelopathic effects may also occur. A more serious disadvantage is often thought to be the difficulties concerned with the practical management of intercropping, especially where there is a high degree of mechanization or where the component crops have different requirements for fertilizers, herbicides, pesticides etc. (Pearce and Gilliver, 1978). These difficulties, however, are typically associated with more developed agriculture; the farmer in a poor or underdeveloped country not only seems well able to handle intercropping but also seems to have a strong inherent preference for it (Willey, 1979). In this respect, it is worth emphasizing that a further justification for more intercropping research is that it is the small farmer of limited means who is most likely to benefit.

Mead and Riley (1981) mentioned, it is important to distinguish between intercropping experiments and competition experiments. They emphasized that, in intercropping, the objectives are essentially agronomic, to find the best way of growing an intercrop combination; an intercropping experiment will normally include a substantial number of experimental treatments for a particular crop mixture. In competition experiments, the objectives are more purely biological, to understand the mechanism of competition, by examining which species or genotypes show competitive benefit when grown in mixtures; a competition experiment will normally include mixtures and pure stands of many species or genotypes, grown under one or a few environments or treatments. This investigation is concentrated on intercropping experiments rather than competition experiments. Therefore, it will not include the competition experiments, although it will be concerned with competition, in the context of intercropping experiments.

While the advantages of intercropping systems are considerable, it is obvious from the literature that our understanding of assessment of a yield advantage in intercropping experiments is small. Part of the problem is that component crops, which are often very different in species or level or yield, are difficult to compare. The other problem arises as the two crop yields in mixed cropping provides different requirements to the farmers. In the present study, my aim is to investigate the validity and their efficiency of the previous models and to get a new model that is suitable for this situation.

II. LITERATURE REVIEW

1. CRITERIA FOR ASSESSING YIELD ADVANTAGES

In many of the experiments reported, intercrops have been achieved by adding together the plant populations used in the pure stand treatments (Evans, 1960; Evans and Sreedharan, 1962; Agboola and Fayemi, 1971). A disadvantage of this system is that the total population of the intercrop is then greater than that of the pure stands. Therefore, if care is not taken to ensure that plant populations are sufficiently high to achieve maximum productivity in the pure stands, the intercrops may give an apparent yield benefit simply because they are the only treatments with adequate population pressure (Willey and Osiru, 1972). De Wit (1960), in studying competition, developed the method of the replacement series. This simply means that an intercrop is formed by replacing a certain proportion of one species by another, thus keeping the total population pressure constant.

It is generally accepted that more than one analysis should be applied to intercropping data (Mead and Stern, 1979). As there is no standard method of analysing data from intercrop and sole crop together, it is sensible to have first separate analyses for the sole crop yields of each crop, for the yields from both the sole and intercropped plots of each crop, and possibly for only the intercropped plot yields (Mead and Riley, 1981). Later an analysis of combined yields of the crops can be considered. As Mead and Riley also mentioned, there has been little work on the analyses of such combined yields.

Three concepts of methods of analysing the combined yield in intercropping systems that are widely used by researchers are the economic analysis, the index of the Land Equivalent Ratio and the bivariate analysis of variance. As the economic analysis is simply weighing each crop yield by each price and then adding together to get the combined yield, it will not be included in this review. The two concepts that will be discussed in II.1.1 and II.1.2 are the Land Equivalent Ratio and the bivariate analysis.

1.1 THE CONCEPT OF THE LAND EQUIVALENT RATIO (LER)

Willey and Osiru (1972) and Huxley and Mainggu (1978) pointed out the danger of comparing a combined intercrop yield with combined sole crop yield on the basis of the same sown proportions, because competition in intercrops usually results in a different proportion of final yields than from sole cropping. To illustrate this argument, Willey (1979) described the three possible patterns of results from replacement-series experiments, which have dominated most research into competition (Fig. 2.1.1.1). When the actual yield of each species is less than expected (Fig. 2.1.1.1a) it is called mutual inhibition, when the yield of each species if greater than expected (Fig. 2.1.1.1b) this is called mutual cooperation, and when one yields more than expected and the other less (Fig. 2.1.1.1c) this is called compensation.

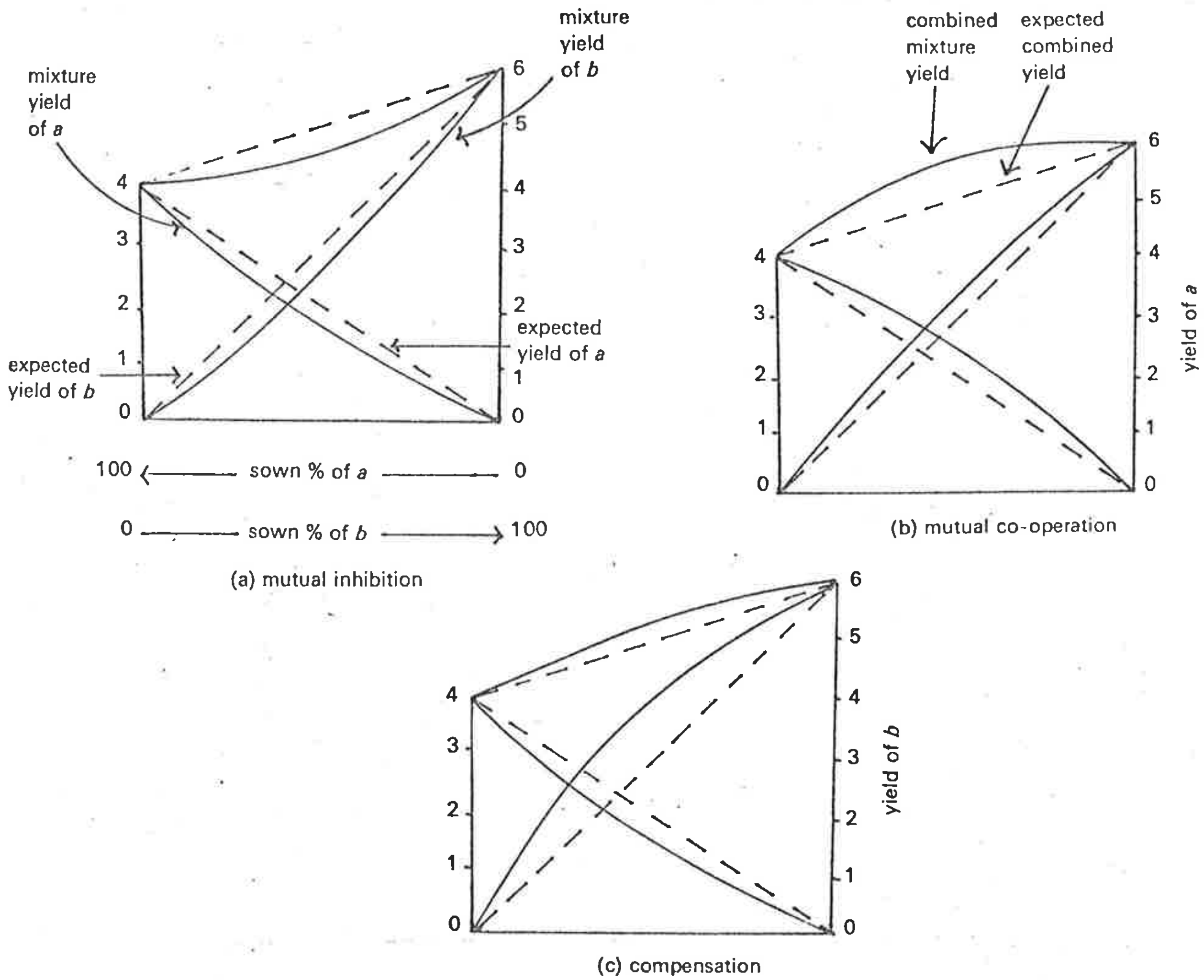


Fig. 2.1.1.1 Type of competition between species (from Willey, 1979).

A disadvantage of this widely-used diagrammatic approach is that with compensation, the apparent overall advantage may be illusory. The "expected" yield in Fig. 2.1.1.1c is calculated assuming that the area is divided into two equal pure stand areas whereas the actual yields of the two species in a 50: 50 mixture could have been achieved by dividing the area into two pure stand areas in the proportion of k and (1 - k), where $k \neq 0.5$. Essentially, when the dominant species, i.e. that yielding more than expected, gives the greater yield, the diagrammatic comparison of intercrop with sole crops is biased in favour of mixing. Of the possible ways to overcome this problem, Willey (1979) concluded that the most generally useful index for expressing the yield advantage is probably the Land Equivalent Ratio (LER), defined as the relative land area required for sole crops to produce the same yield as intercropping. This is essentially the same as the Relative Yield Total (RYT) that has been developed by de Wit's group (de Wit, 1960; de Wit and van den Bergh, 1965; van den Bergh, 1968), though the standardising sole crop yields for the sole crops used as denominators in calculating the LER's are not regarded as necessarily being the yields for the sole crops under the same conditions as the intercrop, but rather as a measure of the maximum achievable sole crop.

Following the notation of Mead and Willey (1980), the Land Equivalent Ratio (LER) can be written

$$LER = L_A + L_B = \frac{M_A}{S_A} + \frac{M_B}{S_B} \qquad (2.1.1.1)$$

where L_A and L_B are the LER's for the individual crops;

M_A the yield of crop A that is intercropped with crop B;

M_B the yield of crop B that is intercropped with crop A;

S_A the yield of sole crop A;

S_B the yield of sole crop B.

Mead and Willey (1980) and Mead and Riley (1981) pointed out that there are two difficulties with the LER's as defined in (2.1.1.1), and both arise from its use as a measure to compare different intercropping situations. Since the LER is defined as a ratio, large values can be obtained because of large yields in intercropping, but also because of small yields in corresponding sole crops. The second difficulty in using LER's as a measure of biological efficiency to compare different situations is the implicit assumption that the harvested proportions of the two crops are exactly those that are required in each situation. Thus, a LER provides a measure of biological efficiency for each genotype combination, but is not always suitable for comparing combinations. Because of these difficulties, Mead and Willey (1980) suggested that, if LER is to be used to compare different situations, one should regard the sole crop yields purely as standardising factors, making it possible to add yields for the two crops. For the purpose of comparing genotypic combinations, it may be sensible to use the same standardising factors for each combination, which leads to SA and SB being defined as maximum or average sole crop yields for the experimental treatments.

Another difficulty of using LER as a measure of the available yield advantage, is that there is an implicit assumption that the yield proportions incorporated in that LER are those required, or acceptable by the farmer, which raises particular difficulties in comparisons between LERs with different yield proportions, a straight comparison implying that either combination of yield proportions is equally acceptable. Mead and Willey (1980) gave as an example, an experiment at ICRISAT on maize/pigeon pea which gave results (kg/ha) for the two best intercrops as follows (Table 2.1.1.1).

Table 2.1.1.1 The result of experiment at ICRISAT for the two best intercrops of maize and pigeonpea (from Mead and Willey, 1980)

	Intercrop 1		Intercrop 2	
	Yield (kg/ha)	LER	Yield (kg/ha)	LER
Intercrop maize	2234	0.66	3130	0.92
Intercrop pigeon pea	896	0.87	571	0.52
Total LER		1.53		1.44
Yield proportion of maize $\left(\frac{L_M}{L_M + L_P}\right)$		0.43		0.63

It could be misleading to argue that Intercrop 1 is better than 2 on the basis of a higher LER, because Intercrop 2 might be preferred if the minimum yield proportion of maize desired by farmers was 0.60. Mead and Stern (1979) and Mead and Willey (1980) calculated the proportion of intercropping (k) for required proportion (p) of crop A and then calculated the effective LER, to overcome this problem:

$$k = \frac{(1 - p)}{pL_B - (1 - p)L_A + (1 - p)} \quad , \text{ if } p > pmax = L_A \qquad (2.1.1.2)$$

$$\text{The effective LER} = \frac{L_B}{(1 - L_A) + (LER - 1)p} \quad . \qquad (2.1.1.3)$$

For $p < pmax$, the formulae are the same, except that A and B are reversed. The comparison then is on the basis of the effective LER instead of the LER itself. If, for each combination, it is assumed that the sole crops included to modify the harvested proportions are the genotypes used in that combination, then those equations become

$$k = \frac{(1 - p)C_A}{pL_B - (1 - p)L_A + (1 - p)CA} \quad . \qquad (2.1.1.4)$$

$$\text{The effective LER} = \frac{L_A C_A}{(C_A - L_A) + (L_A + L_B - C_A)p} \qquad (2.1.1.5)$$

where C_A is the LER value of crop A grown as a sole crop to modify the harvested proportions. In calculating the effective LER, Mead and Willey (1980) assumed that the sole crop areas which are to be mixed with the intercropped area to obtain the required harvest proportions of the two crops will comprise the form of sole crop which gives maximum yield. They also assumed that the maximum sole crop yields are used as the standardising measures in calculating all LER's.

1.2 THE APPROACH USING BIVARIATE ANALYSIS

Multivariate analysis of the results of agricultural experiments in which more than one variable was measured has been proposed before by Quenouille (1950) and Steel (1955), but in circumstances that lead to some prejudice against it. Steel (1955) suggested its use for two successive crops of a perennial species and appeared to imply that in the agricultural context the mean performance of a treatment is of little importance as long as the significance of treatment differences can be established, a view strongly contested in that particular context by Finney (1956). Pearce and Gilliver (1978, 1979) emphasized, however, that while means are obviously important, significant tests have their place as well.

The purpose of bivariate analysis is that the two variates are dealt with, not separately, but in conjunction. In intercropping situations, the difficulty comes from the correlation between the yield of crop 1 (X_1) and that of crop 1 (X_2) (Pearce and Gilliver, 1978, 1979). It cannot be assumed that neither one exactly determined the other, nor that the two were completely independent. There are, in fact, likely to be two contrary forces at work. If a plot contains good soil, it is to be expected that both crops will do well, which imparts a positive correlation to X_1 and X_2. On the other hand, the two crops are in competition, which tends to make the correlation negative, and there is no prior reason for declaring which force will prevail or how much. Pearce and Gilliver (1978, 1979) suggested, partly following Steel's approach, how to analyse intercropping experiments with bivariate analysis. They proposed two different methods which are in fact equivalent.

The model in this approach is in fact the multivariate one. For a randomized complete block experiment, denote the yield in the h^{th} crop for the i^{th} replicate the j^{th} treatment by

$$Y_{ij}^{(h)} = \mu^{(h)} + \rho_i^{(h)} + \tau_j^{(h)} + \xi_{ij}^{(h)} \quad . \qquad (2.1.2.1)$$

Since tests of significance are planned, assume the $\xi_{ij}^{(h)}$ have a joint normal distribution and, for fixed h, are independently distributed with a common variance. Assumptions about the other additive components may be those of the usual models. The other important assumption in bivariate analysis is that the correlation between the yield for the two crops is constant for all treatments, I shall test this later.

Following the same arguments of Pearce and Gilliver (1978, 1979) and Gilliver and Pearce (1983), let the two crops, when analysed, have error variances of V_{11} and V_{22} and let the error covariance be V_{12}. Also let V'_{11} and V'_{22} be the same variances after adjusting each variate by the other, i.e.

$$V'_{11} = V_{11} - V_{12}/V_{22} \qquad (2.1.2.2)$$

$$V'_{22} = V_{22} - V_{12}/V_{11} \quad . \qquad (2.1.2.3)$$

Now form two new variates

$$Y_1 = X_1/\sqrt{V_{11}} \qquad (2.1.2.4)$$

$$Y_2 = (X_2 - V_{12}X_1)/\sqrt{V'_{22}} \quad . \qquad (2.1.2.5)$$

It will be found that these new variaties have error variances equal to one and error covariance equal to zero i.e. they can be treated as if they were independent.

The first method then is to transform all data from X_1 and X_2 to Y_1 and Y_2. The means of the new variates can then be graphed against one another in the usual way to show varying effects. In the other method, the correlation between the original variates X_1 and X_2 is allowed for by the use of skew axes. These approaches are illustrated in Fig. 2.1.2.1.

Using the first method, the point, M, is reached from the origin, O, by going a distance, Y_1, along the horizontal axis at P and then a distance, Y_2, parallel to the vertical. Using the second, it is reached by going a distance $Z_1 = X_1/\sqrt{V'_{11}}$ along the skew axis to Q and then a distance $Z_2 = X_2/\sqrt{V'_{22}}$ parallel to the vertical axis, the angle θ being such that its cosine is the correlation coefficient between X_1 and X_2, i.e.

$$\mathrm{Cos}\theta = \frac{V_{12}}{\sqrt{V_{11}V_{22}}} \qquad (2.1.2.6)$$

By either method, the same point, M, will be reached.

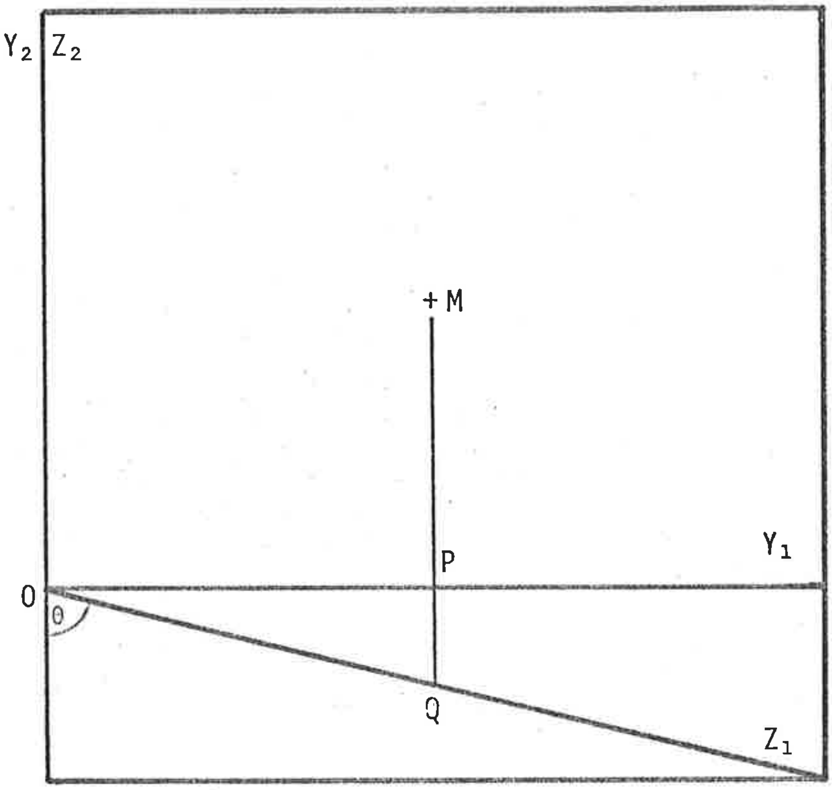


Fig. 2.1.2.1 Diagrammatic scheme for representing the effects of treatments (redrawn from Pearce and Gilliver, 1978).

Both methods have advantages. Since Y_1 and Y_2 are uncorrelated, and have the same variance, it follows that a displacement in one direction is as important as a similar displacement in any other. Hence the standard error of a treatment mean of n values is represented by a distance of $1/\sqrt{n}$ in any direction, and plotted as a circle of radius $1/\sqrt{n}$ on the Y axes. On the other hand, it is easier to think in terms of Z_1 and Z_2 which are only X_1 and X_2 on different scales, the skewness of the axes being a reminder that a change in the value of one implies a change in the other also. Thus, if the correlation between X_1 and X_2 is positive, as was assumed in Fig. 2.1.2.1 for a large Z_1, a large Z_2 is needed to achieve the same value of Y_2. It has been assumed in Fig. 2.1.2.1 that X_1 and X_2 are positively correlated, so that θ lies between 0 to 90 degrees. If the correlation were negative, θ would lie between 90 and 180 degrees, i.e. the skew axis would be above the horizontal one, not below it.

For testing of significance, Pearce and Gilliver derive results ultimately from the work of Wilks (1932) as presented by Rao (1952). The variates of Y_1 and Y_2 have been chosen so that the error variance of each equals one and their covariance equals zero. If there are e degrees of freedom for error, their error sums of squares must equal e and the error sum of products must equal zero. Let the corresponding values for treatments be Γ_{11}, Γ_{22} and Γ_{12} with t degrees of freedom. Then the criteria to be used are

$$U = e^2/B \tag{2.1.2.7}$$

and

$$B = (\Gamma_{11} + e)(\Gamma_{22} + e) - \Gamma_{12} \tag{2.1.2.8}$$

Its significance can be judged by calculating the bivariate F value, which is

$$F = \frac{1 - \sqrt{U}}{\sqrt{U}} \cdot \frac{e - 1}{t} \tag{2.1.2.9}$$

and referring it to ordinary F tables with 2 t degrees of freedom for treatments and 2(e - 1) for error, to see if the treatment points can be regarded as significantly different or not. It will be seen that the bivariate F could have been obtained as

$$\frac{(\sqrt{B} - e)(e - 1)}{te} \quad . \tag{2.1.2.10}$$

However, it can be useful to have a test for the distance between two specified points, analogous to the use of least significant differences. If two arbitrary points are a distance d apart and each is based on n observations, then

$$\Gamma_{11} = \tfrac{1}{2}n\ (\text{difference in values of } Y_1)^2 \text{ , so } \Gamma_{11}\Gamma_{22} - \Gamma_{12}^2 = 0$$

and

$$d = \sqrt{\frac{2(\Gamma_{11} + \Gamma_{22})}{n}} \quad . \tag{2.1.2.11}$$

Consequently,

$$B = e(\tfrac{1}{2}nd^2 + e) \tag{2.1.2.12}$$

and t equals one. (It is assumed that the design is of full efficiency, e.g. in randomized blocks.) With this result, it is possible to use a generalized F test as described above, but a simpler form exists in the case of there being only one degree of freedom in the numerator (Rao, 1952) and that can be used here.

It appears that d is significant if d^2 exceeds

$$\frac{4e\, F_{c,\alpha}}{n(e-1)} \qquad (2.1.2.13)$$

where $F_{c,\alpha}$ is the critical value of F for 2 and (e - 1) degrees of freedom at the significance level α.

A further need may be to find contour lines to join points having the same value when a unit of X_1 is held to be worth α_1 and a unit of X_2 is valued at α_2, i.e. to join points have a total value of

$$c = \alpha_1 X_1 + \alpha_2 X_2 \quad . \qquad (2.1.2.14)$$

Three such points are readily found

1) Let $Y_1 = 0$, then $X_1 = 0$; $X_2 = c/\alpha_2$

   and $Y_2 = c/(\alpha_2 \sqrt{V'_{22}})$

2) Let $Y_2 = 0$, then $X_2 = V_{12}X_1/V_{11}$

$$c = \frac{(\alpha_1 V_{11} + \alpha_2 V_{12})X_1}{V_{11}}$$

and

$$Y_1 = c\sqrt{V_{11}}/(\alpha_1 V_{11} + \alpha_2 V_{12})$$

3) Let $Z_2 = 0$, then $X_2 = 0$; $X_1 = c/\alpha_1$

   and $Z_1 = c/(\alpha_1\sqrt{V'_{11}})$.

To complete this approach, Gilliver and Pearce (1983) presented the graphical assessment of interaction for factorial experiments. Let there be two factors, A and B, each at two levels (1 and 2), i.e. a 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 × B. As in intercropping, we dealt with the bivariate case, the diagram requires at least two dimensions.

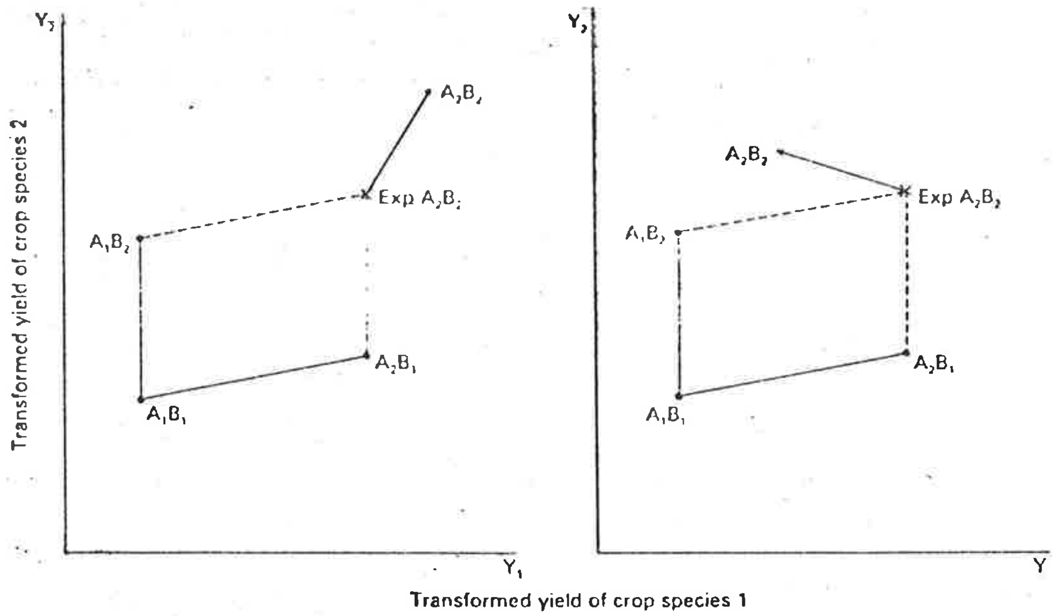


Fig. 2.1.2.2 Two-factor interactions of the same magnitude but with different agronomic implications. (from Gilliver and Pearce, 1983).

Points A_1B_1, A_2B_1, A_1B_2 and A_2B_2 in Fig. 2.1.2.2 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 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. 2.1.2.2 by a solid line capped with an arrow. A circle drawn round the expected A_2B_2 will give the same significance level for interaction. However, the practical interpretation will depend on the actual location of A_2B_2 (eg. in the two cases shown in Fig. 2.1.2.2, 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 more complicated as Fig. 2.1.2.3 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 × 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 × B in the absence of C_1, it will give an expected point for $A_2B_2C_2$.

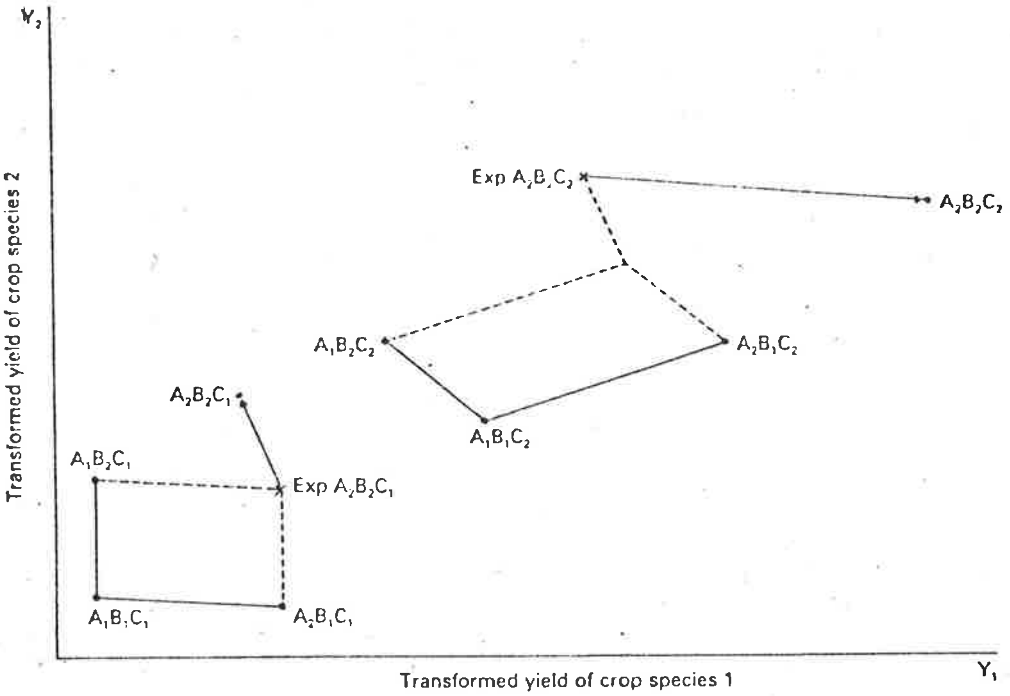


Fig. 2.1.2.3 Graphical representation of data from a three-factor experiment illustrating three-factor interaction. (from Gilliver and Pearce, 1983).

The displacement of the actual point from its expected position will give the three-factor interaction, A × B × C. 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. 2.1.2.3 have different shapes is irrelevant to the estimation of the three-factor interaction, though it may well indicate two-factor interactions such as A × C or B × C. The order of the factors is immaterial; the interactions A × B × C; B × A × C; B × C × A are the same.

As a result of the complexity of this diagram for higher order factorials, the magnitude of interaction would be much better by using the colour graphics rather than black and white paper.

2. CRITERIA FOR ASSFSSSING YIELD STABILITY

It is often suggest that improved stability of yield is one of the major reasons why intercropping continues to be an extremely important practice in many developing areas of the world, especially those areas of greater risk (Aiyer, 1949; Rasmuson, 1968; Yodha, 1979). It also provides different crops from a small land area, e.g. cereal and pulse for a more balanced subsistance diet. The stability is credited to several factors, including disease resistance, increased resistance to lodging, and undefined complementary effects inherent in certain intercropping (Jensen, 1952; Grafius, 1966; Freyman and Maldanado, 1967). As Rao and Willey (1980) said, intercropping could also provide greater stability if its yield advantage compared with sole cropping were greater under stress than nonstress conditions, since this would mean that intercropping yields in seasons of stress would not decrease as much as yields of sole crops.

Three methods that have been used to assess relative stability of yield in intercropping are:

(i) Computing coefficient of variation (Rasmuson, 1968; Rao and Wil.ey, 1980). Both Rasmuson and Rao and Willey concluded that, by calculating the coefficient of variation, intercropping was less variable than sole cropping. However, this approach gives only a relatively simple expression of the variability about the mean yield (Rao and Willey, 1980).

(ii) Adapting the regression technique, which has frequently been used to examine the stability of individual genotypes over a range of environments (Finlay and Wilkinson, 1963; Eberhart and Russel, 1966; Rasmuson, 1968; Briese and Hill, 1973; Rao et al., 1979; Rao and Willey, 1980). Finlay and Wilkinson emphasized that a regression coefficient of unit slope (b = 1) indicates that variety yield is directly proportional to the environmental index (i.e. such a variety has average stability). A completely stable variety (b = 0) would yield the same in all environments. Rao and Willey (1980) drew attention to a major difficulty encountered in the evaluation of intercropping by this approach, namely that comparisons are being made between crops which have very different types and levels of yield. To overcome this problem, Rao and Willey suggested that the different yield levels can be taken into account by considering relative yields, the mean for each crop over all locations being taken as 1. As they emphasized, a further feature of this relative yield approach is that it highlights the yield advantage of intercropping that would commonly be computed using LER, on which basis the response of intercropping was greater than either sole crop.

Despite the possible usefulness of these two approaches (i.e. coefficient of variation and adapting the regression technique), they leave much to be desired because they still do not indicate, in simple pratical terms, what a given level of statistical stability means to a farmer (Rao and Willey, 1980).

(iii) By assuming that a farmer's major concern is to avoid disaster, Rao and Willey (1980), following the idea of Francis and Sanders (1978), estimated the probability of each cropping system failing to provide given disaster levels of monetary returns (Fig. 2.2.1). An additional feature of this mode of presentation is that because the price structures are not static, the price ratio for sorghum: pigeon pea was randomly allocated for each location with the range 1: 1 and 1: 3, though the data could just as easily be presented for any fixed ratio required.

By using this approach, Rao and Willey concluded that at any given disaster level, intercropping showed a much lower probability of failure than either sole crop.

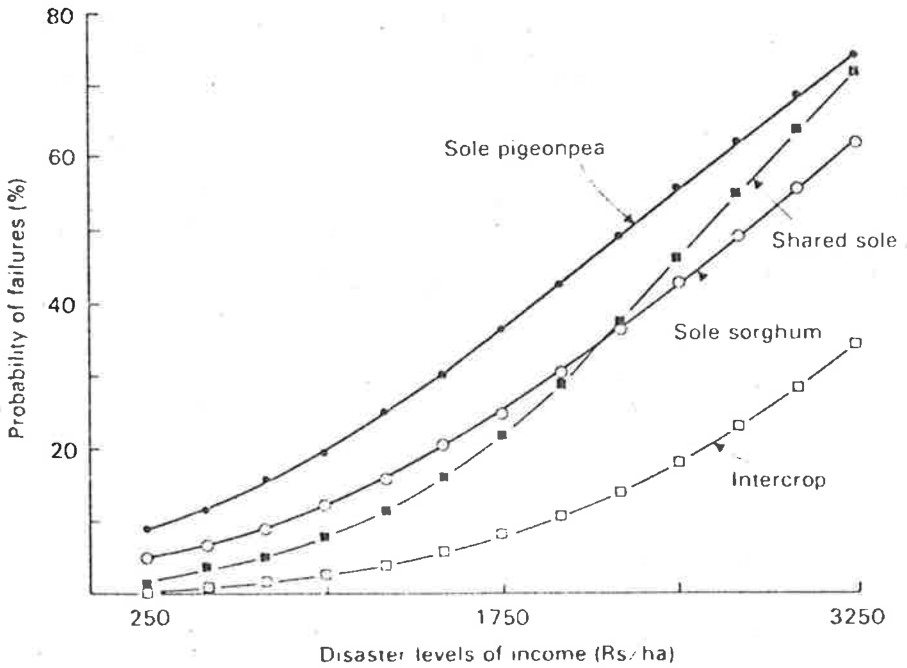


Fig. 2.2.1 Probability of failure for sorghum and pigeon pea in different cropping systems at a given disaster level of income. (from Rao and Willey, 1980).

3. CRITERIA FOR ASSESSING COMPETITION

In studying the development of a community of plant species, it is important to know how each species is affected by its competition with others for space, light, moisture, nutrients and other requisites (William, 1962). As I emphasized earlier, this study is concerned with intercropping experiments, so the models for describing competition that are proposed for competition experiments will not be discussed here. Willey (1979) listed some coefficients that are generally used to describe competition in intercropping experiments. They are Relative Crowding Coefficient, Aggressivity, Competition Index and the Land Equivalent Ratio.

De Wit (1960) proposed a relative crowding coefficient to support the examination in mixture experiments. This coefficient is aimed to describe the degree of competition between species in the mixture. This coefficient was examined in detail by Hall (1974a, 1974b). He assumes that mixtures form a replacement series.

Then

$$k_{ab} = \frac{Y_{ab} \times Z_{ba}}{(Y_{aa} - Y_{ab}) \times Z_{ab}} \qquad (2.3.1)$$

and k_{ab} is defined as the Relative Crowding Coefficient of species a over species b in the mixtures; Z_{ab} and Z_{ba} are the sown proportion of species a (in mixtures with b) and the sown proportion of species b (in mixtures with a) respectively; Y_{aa} and Y_{ab} are the yield of crop a as sole crop and in mixtures with crop b respectively. The values of k for each species, k_{ab} and k_{ba} and the product k_{ab} and k_{ba} are used to describe the level and type of interference occurring between two species. If a species has a coefficient less than, equal to, or greater than one, it means it has produced less yield, the same yield or more yield than expected respectively. The component crop with the higher coefficient is the dominant one. When the two species compete for the same resources, the product of k_{ab} and k_{ba} should be equal to one. If $k_{ab} \times k_{ba}$ is greater than one, a and b may be competing for different resources; the product may then be described as the advantage of the mixture. In contrast, when $k_{ab} \times k_{ba}$ is smaller than one, the mixtures were described as disadvantageous.

McGilchrist (1965) and McGilchrist and Trenbath (1971) proposed another coefficient to describe the degree of competition between the species in the mixtures, i.e. a measure of Aggressivity and it is usually denoted by A

$$A_{ab} = \frac{Y_{ab}}{Y_{aa} \times Z_{ab}} - \frac{Y_{ba}}{Y_{bb} \times Z_{ba}} \qquad (2.3.2)$$

where Y_{aa}, Y_{ab}, Y_{ba}, Z_{ab} and Z_{ba} are the same as in relative crowding coefficients, described earlier.

An Aggressivity value (A_{ij}) of zero indicates that the component species are equally competitive. For any other situation, both species have the same numerical value but the sign of the dominant species will be positive and that of the dominated negative; the greater the numerical value, the bigger difference in competitive abilities and the bigger the difference between actual and expected yields.

Donald (1963) suggested the competition index to describe whether the association of the two species in the mixtures is beneficial or not. The basic process is the calculation of two equivalence factors, one for each component species. For species a, the equivalence factor is the number of plants of species a which is equally competitive to one plant of species b. In generalized terms, the competition index is

$$\frac{(N'_A - N_A)(N'_B - N_B)}{N_A N_B} \qquad (2.3.3)$$

where N_A plants of species A compete with N_B plants of species B on a unit area, and the yield per plant of A in the mixture equals the yield per plant of N'_A in a pure stand on a unit area and the yield per plant of B in the mixture equals the yield per plant of N'_B plant in pure stand on a unit area. If the competition index is less than one, there has been an advantage of mixing. Conversely, if the index is greater than one, a harmful association would have been indicated. Donald emphasized that in order to determine the competition index, it is necessary to grow each species in pure stand at a sufficent range of densities to enable a density-yield curve to be constructed. As a result of that condition, the use of competition index in intercropping experiments has been small, though Lakhani (1976) (in Willey, 1979) suggested using some quantitative relationships between yield and plant population (Willey and Heath, 1969) in improving estimation of the yield in a certain density.

Willey (1979) suggested that comparisons between individual LERs (L_A and L_B) can indicate competitive effects. He compared the relative crowding coefficient, the aggressivity and the LER for experiments of sorghum and millet intercrops. The conclusion of his study is that both the crowding coefficient and the LER values show which combination does, or does not, give yield advantages; the aggressivity values are not able to do this. As Willey emphasized, a major drawback of the crowding coefficients is that they do not give a simple indication of the actual magnitude of any yield advantage. Willey and Rao (1980) pointed out that, although the aggressivity has the merit of trying to relate the yield changes of both crops, it might be more meaningful to calculate the ratio of the equations (2.3.2) in terms of ratio and it is called the competitive ratio.

$$CRa = \left(\frac{Y_{ab}}{Y_{aa} \times Z_{ab}}\right) \Bigg/ \left(\frac{Y_{ba}}{Y_{aa} \times Z_{ba}}\right) = \left(\frac{L_A}{L_B}\right) \Bigg/ \left(\frac{Z_{ab}}{Z_{ba}}\right) \qquad (2.3.4)$$

The competitive ratio term is therefore simply the ratio of the individual LERs of the two component crops, but correcting for the proportions in which the crops were initially sown. Willey and Rao emphasized that the CR value gives the exact degree of competition by indicating the number of times one crop is more competitive than the other. Moreover, they said that in contrast to the problems experienced with the method above, this relationship will hold true whatever level of yield advantage is being achieved by intercropping (i.e. for any total LER value).

4. CONCLUDING REMARKS

To compare or assess the yield advantage and its relation factors in intercropping experiments, a study has to be made, both in the validity of the models that have been proposed and its efficiency in the various types of these experiments.

Several problems must be overcome in this study. The first one, as mentioned earlier, is to test the validity of the models and their efficiency. The methods that have been discovered are still not satisfactory from either the agronomist's or the statistician's points of view. For example, the

Land Equivalent Ratio (LER) is designed to solve this problem but the LER, calculated at any single combination of plant populations, is not, in itself a useful criterion. At very wide spacings, such as are often found in peasant agriculture, the plants will be so far apart that they are virtually free-standing, under which circumstances the LER is 1 and intercropping offers no technical advantages, apart from perhaps the case of tillage, although social and economic considerations may be overriding. On the other hand, the highest LER value sometimes does not mean anything to the farmer due to the LER itself not allowing for the relative merit of each crop. Even the effective LER does not help in this situation because the calculation of the required yield proportion by a farmer depends also on the LER of the other crop. Therefore, the required yield proportion calculated by that method will not mean anything to the farmer. The requirements of farmers actually comprise a certain amount of a major crop for staple food and some yield of a secondary crop, that would be sold for cash. The other basic problem, as Mead and Willey (1980) emphasized, is that the method of standardization used in calculating LER should vary according to the form and objective of the experiment. Huxley and Maingu (1978) said that all intercrop yields should be compared with the sole crop at its optimum population and spacing. As Mead and Riley (1981) pointed out very clearly, more statistical work is needed on the choice of standardization method in calculating the LER. Another consideration for this approach (i.e. LER) is that, because LER itself is a proportional measure, the assumption of normality does not generally hold, therefore the analysis of variance is not appropriate for such data without transformation.

The limitation of the bivariate analysis is the assumption that the correlation between the yield for the two crops is constant for all treatments. In intercropping experiments, more complex situations could occur. As Pearce and Gilliver (1978) mentioned, the correlation coefficient for both crops could be positive or negative, depending on the conditions of the field.

There are some limitations in the three concepts that have been used on stability analysis. A limitation of the coefficient of variation approach is that the calculations are based only on the mean yield of each experiment, so that the variability within experiments is ignored (Rao and Willey, 1980). On the regression approach, it should be emphasized that there can be problems in deciding which cropping system should be used to calculate the environmental index. Further, in this approach, the assumption of linearity between the environmental index and yield is difficult to accept (Knight, 1970), though non-linear regression could be used instead. The monetary approach is limited by the fluctuations of the market.

On the analysis of competition in intercropping, the limitation of the Relative Crowding Coefficient k_{ab} is that in its original form this compared, for any given species, the actual yield per plant in a mixture with an expected yield per plant which would be achieved if the species experienced the same degree of competition in mixtures as in pure stands. Because k_{ab} was based on yield per plant, however, population pressure had to be constant across mixtures and pure stands and it was thus proposed only for use with replacement mixtures and will not be appropriate for investigations of spatial arrangements (Willey and Rao, 1980). The limitations of Aggressivity is that it is based simply on different levels of yield advantage. Willey and Rao (1980) gave an example of a range of situations sown with an initial area allocation of 50: 50 but achieving relative yield or LERs values of 0.60: 0.40; 0.70: 0.50; 0.80: 0.60 etc. These would all give the same Aggressivity value for the first crop: 0.20. And yet it is difficult to argue that the competitive ability of the first crop, relative to the second crop is constant across all these conditions. The competition index has its own limitations, since the sole crop treatments have to be present at a range of plant populations, so that equivalent plant numbers can be estimated. Willey (1979) pointed out that this estimation is not a very accurate procedure, though Lakhani (1976) (in Willey, 1979), has suggested it can be improved by using some quantitative relationship between yield and plant population (Willey and Heath, 1969). The concept of competitive ratio is also limited to the same extent that the concept of LER is limited, as it is actually just the ratio of the LER.

In this study, attempts were made to analyse or evaluate intercropping experiments (i.e. measure of yield advantage, measure of yield stability and measure of competition function). The study includes testing the validity and the efficiency of the previous models over a wide range of intercropping from Indonesia and also develops alternative models.

III. SOURCES OF DATA

1. PROBLEMS WITH SIMULATED DATA

For the purpose of testing statistical methods, simulated data have many valuable properties: models and probability distributions are known ; repeatability is complete; cost is very low; and virtually any desired property of actual data may be simulated. However, for the simulated data to be relevant to the real world, they must be based on the properties of real experiments, and very few published data are available. Furthermore , not all the published work relates to cropping systems as they are actually used in countries such as Indonesia. For this reason, simulation was not used on a large scale, though programs simulating mixed cropping experiments were developed, an example being shown in Appendix A. Experience with these methods, essentially those of Mayo (1975), was gained in trials of some statistical methods suggested for use in quantitative genetics, and the results are shown in the two published papers in Appendix B, these statistical methods not being relevant to mixed cropping systems.

The major source of data then was the extensive series of experiments collected from experimenters after detailed discussion with them, for which purpose the author visited Indonesia for two months.

2. DESCRIPTION OF EXPERIMENTS

These experiments were obtained from the Research Institute for food crops at Bogor, Sukamandi, Lembang and Malang, Sugar Experiment Station at Pasuruan, and the Faculty of Agriculture at Brawijaya University Malang , Indonesia. Experimenters and authors are noted in the Acknowledgments; a list of technical report is included in the references. In general, the aims of these experiments can be divided into two catagories.

The first one was to determine cropping combinations which would maximize the combined mixed yield and to ensure that in some sense this exceeded the maximum sole crop yield. Those researches were based on the knowledge that farmers usually need to grow more than one crop, e.g. to satisfy dietary requirements or to guard against environmental risks. Therefore, most of them are intercropping between staple food crops and legumes. This covers experiment 1 to experiment 38.

The second type of experiment was aimed to maximize full yield of a main crop with some additional yield of one or more other crops. All experiments used intercropping of sugar-cane as a main crop and peanut, soybean, maize, tomatoes, onion etc. as minor crops. The background of those experiments was a government policy. The Indonesian government wants to change the management of sugar-cane from sugar factories to farmers on their own land. It used to be the case that sugar factories grew sugar-cane for their own requirements by renting farmers' land, but now the government wants farmers to grow sugar-cane on their own land and sell it to the factories. The problems are on the one hand that farmers do not want to diminish their own supplies of staple food, vegetables, etc. or wait for payment from growing sugar-cane even though this can bring much benefit. On the other hand, the factories do not want a shortfall of raw material (i.e. sugar-cane) through dependence on sugar-cane grown by farmers. Therefore, those experiments were aimed to get full yield of sugar-cane and some additional yield of secondary crops. These experiments appeared as experiments 39 to 51.

The physical layout of some experiments and the plant samples taken appear in Figs. 3.2.1, 3.2.2, 3.2.3 and 3.2.4.

Details of experiments are as follows:

Experiment 1

There were six treatments that were arranged in a Randomized Complete Block Design with six replicates. There were four intercropping systems of cassava and peanut with different proportions of peanut (i.e. 25%; 50%; 75% and 100% peanut) (see Fig. 3.2.1). There were also sole cassava and sole peanut. In the experiment, the cassava cv. Faroka and the peanut cv. Gajah were used. The cassava was grown at a recommended density of approximately 13,000 plants per hectare and peanut of 100% approximately 320,000 plants per hectare. Within the experiment, between rows of cassava were grown either one row or two rows or four rows of peanut depending on the proportions of peanut. The plot size was $(12 \times 4)m^2$.

Experiment 2

This set of data came from a cassava and peanut or sweet potatoes intercropping experiment. There were sole cassava (100%), sole peanut (100%), sole sweet potatoes (100%) and six intercrop treatments. The intercrops were cassava (150%) + peanut (25%), cassava (100%) + peanut (50%), cassava (48%) + peanut (66.66%), cassava (150%) + sweet potatoes (25%), cassava (100%) + sweet potatoes (50%) and cassava (48%) + sweet potatoes (83.33%). The planting distance of cassava at 150%, 100% and 48% were 100 × 80cm, 100 × 120cm and 100 × 250cm respectively. The peanut at 25%, 50% and 66.66% were 25 × 40cm, 25 × 20cm and 25 × 15cm respectively. The sweet potatoes at 25%, 50% and 83.33% were 100 × 100cm, 100 × 50cm and 50 × 60cm. In the experiment, the cassava cv. Faroka, the peanut cv. Gajah and sweet potato cv. Tumpluk were used. The design was a Randomized Complete Block with four replicates and the plot size was $(18 \times 12)m^2$.

Experiment 3

This experiment involved intercropping between cassava and either peanut or soybean or sesame. There were nine treatments of intercropping systems and four sole crop treatments (i.e. cassava, peanut, soybean and sesame) that were arranged in a Randomized Complete Block Design with three replicates. The intercropping treatments were combinations of three different secondary crops (A_i) (i.e. either peanut, soybean or sesame) and three different proportions (B_j) of each secondary crop that were intercropped with cassava at the same population densities. The distance of cassava was 100 × 75cm and peanut at 50%, 100% and 125% were 25 × 45cm, 25 × 25cm and 25 × 20cm respectively. The planting distance of soybean at 50%, 100% and 120% were 20 × 60cm, 20 × 30cm and 20 × 24cm respectively. The planting distance of sesame at 70%, 100% and 125% were 25 × 80cm, 25 × 60cm and 25 × 50cm respectively. The cassava cv. Faroka, the peanut cv. Kidang, the soybean cv. Davros and the black sesame were used. The plot size was (18 × 12)m^2.

Experiment 4

A rather similar experiment to experiment 3 was carried out for different secondary crops, intercropped with cassava. There were also nine treatments in the intercropping systems and four sole crop treatments (i.e. cassava, broad bean, sweet potatoes and upland rice). Therefore, the nine treatments of intercropping systems were combinations of three different secondary crops (A_i) and three different proportions (B_j) of each secondary crop. The planting distance of cassava was 100 × 75cm and broad bean at 44%, 100% and 133% were 25 × 15cm, 25 × 20cm and 25 × 45cm respectively. The planting distance of sweet potatoes at 74%, 100% and 200% were 25 × 15cm, 25 × 30cm and 24 × 40cm respectively. The upland rice at 40%, 100% and 133% were 20 × 15cm, 20 × 20cm and 20 × 50cm respectively. The cassava cv. Faroka, the broad bean local genotype, the sweet potato cv. Tumpluk and the upland rice cv. IR.36 were used. The design was a Randomized Complete Block Design with three replicates and the plot size was (8 × 7.5)m^2.

Experiment 5

This experiment assessed intercropping between cassava and upland rice.

The four intercrops of cassava and upland rice with different times of planting of cassava (i.e. either at the same time as upland rice (a) or 20 days later (b) or 40 days later (c) or 60 days later (d)). There were also sole cassava and sole upland rice. The planting distance of cassava was 250 × 50cm and upland rice was 25 × 15cm. The cassava cv. Faroka and the rice cv. Bicol were used. The design was a Randomized Complete Block with six replicates and the plot size was (12 × 7.5)m².

Experiment 6

There were six treatments in the intercropping systems and four sole crop treatments that were arranged in a Randomized Complete Block Design with three replicates. The intercropping treatments were combinations of two different densities of maize (A_i) (i.e. with planting distance of 80 × 30cm and 100 × 30cm) and three different doses of Nitrogen fertilizer (B_j) (i.e. Nitrogen of 60kg, 120kg and 180kg per hectare) on the maize which was intercropped with peanut. The sole crop treatments were sole peanut, sole corn (with Nitrogen 60kg/ha), sole corn (with Nitrogen 120kg/ha) and sole corn (with Nitrogen 180kg/ha). The planting distance of peanut was 20 × 30cm and sole maize at high density of maize intercropped was 100 × 30cm and low density of maize intercropped was 160 × 130cm. In the experiment, the maize cv. Kretek and the peanut cv. Gajah were used. The plot size was (8 × 6)m².

Experiment 7

This experiment was another maize and peanut intercrop system with Nitrogen fertilizer treatments. There were 12 treatments: sole peanut, maize and the intercrop, with each of them by four different doses of Nitrogen fertilizer (i.e. 0kg, 45kg, 90kg and 135kg of Nitrogen per hectare). The planting distance of maize was 100 × 30cm and peanut was 20 × 30cm. The maize cv. Kretek and the peanut cv. Gajah were used in the experiment. The experiment was arranged in a Randomized Complete

Block Design with four replicates. The plot size was (5 × 6)m².

Experiment 8

This experiment was on intercropped maize and mungbean. There were 14 treatments arranged in a Split Plot Design and one sole maize with three replicates. The main plot treatments were combinations of two different planting systems (A_i) (i.e. either mungbean monoculture or intercropping with maize) and the sub plot treatments were seven genotypes of mungbean (B_j) (i.e. No. 129, No. 423, cv. Bhaliti, TM100, TM106, No. 467 and No. 438) that were intercropped with maize. The maize cv. Harapan was used in the experiment with planting distance 200 × 40cm. The planting distance of mung bean was 40 × 20cm. The plot size was (7.0 × 4)m².

Experiment 9

This experiment was rather similar to experiment 8; the differences being in the secondary crop. This experiment also had 14 treatments as combinations of two factors, two different planting systems (A_i) (i.e. either monoculture of soybean or intercrop with maize) and seven different genotypes of soybean (B_j) (i.e. cv. Orba, cv. Imp. Pelican, No. 1290, No. 1343, CKI-10, CKI-11 and No. 1682) intercropped with maize. There were also sole maize of cv. Harapan with planting distance of 200 × 40cm. The planting distance of soybean was 40 × 20cm. The design and number of replications were also the same as in experiment 8. The plot size, however, was different: (7.0 × 6.8)m².

Experiment 10

The aim of this experiment was to examine the effect of row direction of planting (A_i) (i.e. north-south versus east-west) in combination with six different planting systems (B_j): sole maize, sole soybean and four intercropping plans with different within-row distances of maize (i.e.

200 × 20cm, 200 × 40cm, 200 × 60cm and 200 × 80cm). The planting distance of soybean was 40 × 20cm with 2 plants per hill. The maize cv. Arjuna and soybean cv. Orba were used in the experiment. This experiment was arranged in a Randomized Complete Block Design with three replicates. It was conducted in the rainy season of 1980/1981 with plot size (4.8 × 6.8)m².

Experiment 11

The replication of experiment 11 was conducted with the same treatments and location as experiment 10, but in the dry season of 1981.

Experiment 12

This was an intercropping experiment on maize and different genotypes of soybean. There were 12 intercropping treatments and eight sole crop treatments. The intercropping treatments were combinations of two different genotypes of maize (A_i) (i.e. cv. Harapan and cv. Kretek) and six different genotypes of soybean (B_j) (i.e. cv. Orba, B1667, No. 1343, CKIV/6, CKII/34 and No. 1400B). The sole treatments were two maize and six soybean as in intercrop. The planting distance of corn was 200 × 40cm for cv. Harapan and 160 × 30cm for cv. Kretek. The planting distance of soybean was 40 × 12.5cm and it was grown 2 plants/hill. The design was a Randomized Complete Block with three replicates and the plot size was (8 × 2.5)m².

Experiment 13

This experiment was rather similar to experiment 12, but with a different secondary crop. The secondary crop was any of six different genotypes of mung bean (i.e. No. 129, TM.106, cv. Bhakti, TM.100, TM.72 and Jambe Gede local). Therefore, there were also 12 intercropping treatments and eight sole crop treatments. The genotypes and planting distance of maize were the same as in experiment 12. The planting distance of mung bean was 20 × 20cm. It was conducted in the dry season of 1978. The design was a Randomized Complete Block with three replicates. The plot size was (8 × 2.5)m².

Experiment 14

This experiment was similar to experiment 13, but was conducted in the dry season of 1979.

Experiment 15

There were two different population densities of maize (A_i) (i.e. approximately 25,000 and 50,000 plants per hectare) and four different planting distances (B_j) of maize (i.e. 200 × 20cm with one plant, 200 × 40cm with two plants, 200 × 60cm with three plants, and 400 × 20cm with two plants per hill). The population density of the peanut was the same for those two populations of maize, but different planting distances were used (i.e. 20 × 12cm with one plant per hill for low densities of maize, and 140 × 12cm with two plants per hill for high densities of maize). Therefore, there were eight sole maize treatments and two sole peanuts with different planting distances as intercrops. The maize cv. Harapan and peanut cv. Gajah were used. The design was a Randomized Complete Block with three replicates. The plot size was (6 × 5)m^2.

Experiment 16

This experiment was designed to assess the effect of weeding methods and planting systems of peanut and corn intercrop.

Four methods of weeding (A_i), mainly weeding by hand, weeding by hock-hoe, weeding by herbicide and no weeding were combined with three planting systems (B_j), either sole peanut or intercrop peanuts and maize or sole maize. Planting distance of maize was 160 × 30cm and peanut was 40 × 20cm. The maize cv. Kretek and the peanut cv. Gajah were used in this experiment. The design was a Randomized Complete Block with three replicates and the plot size was (6 × 5)m^2.

Experiment 17

This experiment was aimed to assess the effect of date of planting of peanut and maize in intercropping systems. There were eleven treatments (as in table below) arranged in a Randomized Complete Block with four replicates.

G_0:	sole peanut
G_0K_{-55}:	peanut + maize; peanut sown 55 days after sowing of maize
G_0K_{-69}:	peanut + maize; peanut sown 69 days after sowing of maize
G_0K_{-14}:	peanut + maize; peanut sown 14 days after sowing of maize
G_0K_0:	peanut + maize; peanut and maize sown at the same time
G_0K_{14}:	peanut + maize; peanut sown 14 days before sowing of maize
K_{-55}:	sole maize 55 days before G_0
K_{-14}:	sole maize 14 days before G_0
K_0:	sole maize at the same time as G_0
K_{14}:	sole maize 14 days after G_0

The planting distance of maize was 160 × 30cm and peanut was 40 × 20cm. In the experiment, the maize cv. Kretek and the peanut cv. Gajah were used. The plot size was (8 × 6)m^2.

Experiment 18

This experiment was aimed at assessing the effect of date of planting (A_i) of peanut and population density of maize (B_j) on peanut and maize intercropping. There were nine combinations of intercropping systems and four sole crops as control treatments. The intercropping treatments were three different dates of planting peanuts (i.e. 0 days, 14 days later and 28 days later after sowing of maize), that were combined by three different population densities of maize (i.e. 166, 666, 83,333, and 55,555 plants per hectare). The sole crops were three sole maize treatments with differences in population density and one sole peanut. The maize cv. Kretek and the peanut cv. Gajah were used in this experiment. The design was a Randomized Complete Block with four replicates and plot size of $(5 \times 2)m^2$.

Experiment 19

This experiment also involved intercropping of peanut and maize. There were eight treatments, a combination of three factors at two levels. The first factor was population density of maize (A_i) (i.e. 60,000 and 90,000 plants per hectare). The second factor was two different genotypes (B_j) of maize (i.e. cv. Harapan and cv. Kretek) and the third one was planting systems (C_k) of maize (i.e. either sole maize or intercrops with peanuts). The peanut cv. Gajah was used at a planting distance of (40×10)cm. Sole peanut was also a control.

The design was a Randomized Complete Block with three replicates and the plot size was $(5 \times 3.2)m^2$.

Experiment 20

This experiment was rather similar to experiment 19. There were three factors, the first, two planting systems (A_i) of either sole maize or intercrop of maize and peanut, the second being three different genotypes of maize (B_j) (i.e. maize cv. Bordek, cv. Kretek and cv. Harapan), and third one being two densities of maize (i.e. 50,000 and 100,000 per hectare). There was also a sole peanut control. The design and replication were similar to experiment 19. The peanut cv. Gajah were used with a planting distance of 40×20cm. The plot size was $(5 \times 2)m^2$.

Experiment 21

There were eight intercropping combinations and two treatments of sole maize arranged in a Randomized Complete Block with three replicates. The intercropping treatments were combinations of planting systems (A_i) (i.e. either sole crop or intercrop of maize, secondary crops (B_j) (i.e. either rice or soybean) and insecticide treatments (C_k) (i.e. without spraying and with spraying of insecticide). In the experiment, the maize cv. Harapan, the rice cv. Bicol and the soybean cv. Orba were used. The planting distance of maize was 100 × 20cm, rice was 20 × 20cm and soybean was also 20 × 20cm. The sole crop treatments were sole maize with and without spraying of insecticide. The plot size was (9 × 4.5)m².

Experiment 22

There were sixteen treatments arranged in a Split Plot Design with three replicates. The main plot treatments were combinations of four different maize genotypes (A_i) (i.e. cv. Harapan, cv. HPH-68, cv. Kretek and cv. Madura local) and two planting systems (B_j) of maize as either sole or intercrop with soybean). The two sub-plot treatments were leaf cuttings of maize, i.e. with or without leaf cuttings. Sole soybean was also a control. The planting distance of maize was 180 × 40cm for cv. Harapan and cv. HPH-68 and cv. Kretek and 120 × 20cm for cv. Madura local. The soybean cv. Orba was used with a planting distance of 30 × 15cm. The plot size was (7.2 × 4)m².

Experiment 23

This experiment was the same as experiment 22, but conducted at a different station. Experiment 23 was conducted in Bogor, experiment 22 in Trenggalek.

Experiment 24

This experiment was also aimed to determine the effect of leaf cutting of maize on intercropping of maize and upland rice and it was conducted in a Split Plot Design with three replicates. The aim of leaf cutting of maize was mainly to reduce the effect of shading on the second crop. However, leaf cutting also affects the yield of maize. Therefore, it is necessary to know the time of leaf cutting that doesn't affect maize yield. The main plot treatments were combinations of three different maize genotypes (i.e. cv. Harapan, cv. Kretek and cv. Madura local) and two planting systems of maize by itself or intercropping with upland rice. The sub-plot treatments were three levels of leaf treatments on maize (i.e. no leaf cutting, leaf cutting when the maize had 5 leaves and leaf cutting at 25 days after silking). The planting distance of maize was 200 × 40cm for cv. Harapan and cv. Kretek and 120 × 20cm for cv. Madura local. In the experiment upland rice cv. IR-36 were used with planting distance of 20 × 20cm. The plot size was (8 × 3.0)m².

Experiment 25

There were 10 treatments of intercropping systems arranged in a Randomized Complete Block with three replicates. The treatments were 10 different genotypes of peanut (i.e. cv. Kidang, No. AH-5, No. AH-8, No. AH-9, No. AH-10, No. RR-1, No. RR-2, No. RR-3, No. RR-4, cv. local) intercropped with corn. The maize cv. Harapan had a planting distance of (200 × 50cm) and peanut (40 × 10cm). Neither sole peanut nor sole maize were grown in this experiment. Plot size was (8 × 4)m².

Experiment 26

This experiment was rather similar to experiment 25. There were also ten intercropping combinations arranged in a Randomized Complete Block. The intercropping systems were ten different genotypes of upland rice (i.e. cv. Gata, cv. IR-36, cv. IR-42, cv. GH-77, cv. BP1-76, cv. IR-206, cv. B295-TB9, cv. B.981, cv. IET-144, and cv. local). The maize cv. Harapan with planting distance of 200 × 50cm and 30 × 15cm of upland rice were used in this experiment. Either sole upland rice or sole maize was not available in this experiment. The plot size was (8 × 6.0)m².

Experiment 27

This experiment was the same as experiment 26, but conducted at a different station. Experiment 26 was conducted at Tulang Bawang, but this experiment was conducted in Baturaja. The plot size was (8 × 6.0)m².

Experiment 28

This experiment was the same as experiments 26 and 27, but conducted at a different station, namely at Way Abung. The plot size was also (8 × 6.0)m².

Experiment 29

The experiment was rather similar to experiment 25 conducted with 11 different genotypes of soybeans (i.e. cv. 1290 Taichung, No. 1667, No. 1343/1611-3-1, No. CK1V-6, No. 1682, No. CKI-10, No. CKI-11, No. CKII-34, cv. Orba, cv. Imperial Pelican, and No. 1400B) intercropped with maize cv. Harapan. The design was also a Randomized Complete Block with three replicates. Neither sole soybean nor sole maize was used in this experiment. Planting distance of maize was 200 × 50cm and soybean was 40 × 25cm. The plot size was (6.0 × 4.0)m².

Experiment 30

This experiment was aimed to assess the effect of management of research and different genotypes of upland rice on maize and upland rice intercropping. There were 20 treatments arranged in a Split Plot Design with three replicates. The main plot treatments were two different management methods (A_i) (i.e. managed by a researcher and managed by a farmer). The sub plot treatments were ten different genotypes of upland rice (B_j) (i.e. IET-144, cv. local, IR-36, cv. Gata, IR-2061, BPI76, No. 981, B.295, GH-77, IR-42). The main cv. Harapan with the planting distance of 200 × 50cm and upland rice of 30 × 15cm were used in this experiment. The plot size was (6.0 × 4.0)m².

Experiment 31

There were twelve treatments of intercropping of soybean and maize systems arranged in a Randomized Complete Block. The treatments were combinations of three different maize genotypes (A_i) (i.e. cv. Harapan, cv. Kretek, and cv. Randu) and four planting distances of maize (i.e. 220 × 40cm, 200 × 40cm, 180 × 40cm, 160 × 40cm) for cv. Harapan or (180 × 30cm, 160 × 30cm, 140 × 30cm, 120 × 30cm) for cv. Kretek or (140 × 20cm, 120 × 20cm, 100 × 20cm, 80 × 20cm for cv. Randu). The soybean cv. Orba with spacing 20 × 20cm was used in the experiment. Neither sole soybean nor sole maize was grown in this experiment. The number of replications was three and plot size was (8.0 × 3.0)m².

Experiment 32

This experiment was aimed at assessing the effect of nitrogen fertilizer on corn and soybean intercropping systems. There were seven treatments (as in table below), arranged in a Randomized Complete Block design with three replicates. The maize cv. Harapan with planting distance of 160 × 20cm and soybean cv. Orba with planting distance 30 × 10cm were used in the experiment. The plot size was (6.0 × 6.7)m².

Treatments	Nitrogen (kg/ha) Maize	Soybean
a	120	0
b	100	20
c	80	40
d	60	60
e	40	80
f	20	100
g	0	120

Experiment 33

This experiment assessed intercropping between cassava and peanut. The twelve treatments were combinations of two different doses of nitrogen on peanut (A_i) (i.e. 0kg, and 45kg of nitrogen per hectare) as main plot treatments and six different doses of nitrogen on cassava (B_j) (i.e. 0-0-0 kg, 0-30-60kg, 30-30-60kg, 60-30-60kg, 90-30-60kg, and 120-30-60kg of NPK per hectare) as sub-plot treatments. The design was a Split Plot with three replicates. The cassava cv. Faroka with planting distance 200 × 50cm and peanut cv. Gajah with planting distance of 20 × 20cm were used. The plot size was (8.0 × 3.0)m².

Experiment 34

There were 24 treatment combinations of maize and sweet potatoes arranged in a Split Plot Design with three replicates. The main plot treatments were two different genotypes of maize (A_i) (i.e. cv. Harapan and cv. Madura local). The twelve sub plot treatments were combinations of two different planting systems of maize (B_j) (i.e. either corn was grown on hills of sweet potatoes or it was grown between hills of sweet potatoes) and six different combination doses of nitrogen phosphorus and potassium (C_k) (as in table below). The sweet potato cv. Tumpluk had planting distance 100 × 25cm and for maize it was 100 × 50cm for cv. Harapan, and for cv. Madura (a local variety) it was 100 × 25cm. The plot size was (5.0 × 4.0)m².

	Sub plot treatments		
Planting systems	(Nitrogen	Phosphorus	Potassium) kg/ha
Corn grown on hills of sweet potatoes	100	50	60
	150	50	60
	100	50	75
	150	50	75
	100	50	100
	150	75	100
Corn grown between hills of sweet potatoes	100	50	60
	150	50	60
	100	50	75
	100	50	75
	100	50	100
	150	75	100

Experiment 35

This experiment was rather similar to experiment 34. The 24 treatments of maize and sweet potato combinations, were arranged in a Split Plot Design with three replicates. The main treatments were again the two different genotypes of maize (A_i) (i.e. cv. Harapan and cv. Madura local). The sub treatments were combinations of three different doses of nitrogen (B_j) (i.e. nitrogen 0kg/ha, 60kg/ha and 90kg/ha) on sweet potatoes and four planting systems of corn (C_k) (i.e. maize was grown on the middle of the hill, on the east side of the hill, on the west side of the hill, or between hills of sweet potatoes) corresponding to north versus south. Planting distances of maize and sweet potatoes and genotypes of sweet potatoes were the same as experiment 34. The plot size was also (5.0 × 4.0)m^2.

Experiment 36

There were 30 treatments arranged in a Split Plot Design with three replicates. The main plot treatment was leaf cutting of maize (A_i) (i.e. without leaf cutting and with leaf cutting). The sub plot treatments were combinations of three different maize genotypes (B_j) (i.e. cv. Madura local, cv. Randu, and cv. Arjuna) and five different planting distances (C_k) (i.e. 100 × 20cm, 120 × 20cm, 140 × 20cm, 160 × 20cm and 180 × 20cm on intercrop of maize and upland rice). The upland rice cv. IR.36 with planting distance of 20 × 20cm was used. The plot size was (7.0 × 3.0)m^2.

Experiment 37

This experiment was aimed to assess the effect between row distance of maize (A_i) (i.e. 80 × 30cm, 160 × 30cm and 200 × 30cm) and five different times of leaf cutting of maize (B_j) (i.e. none, at 7 days, 12 days, 17 days, and 20 days after silking) on maize and upland rice intercropping systems. Therefore, there were 15 intercropping treatments that were arranged in a Randomized Complete Block design with four replicates. The maize cv.

Harapan and the upland rice cv. IR.36 with planting distance of 20 × 20cm were used in this experiment. The plot size was (8.0 × 4.5)m².

Experiment 38

This experiment was the same as experiment 37, but different in season of planting. The experiment 37 was conducted in the rainy season, this experiment was conducted in the dry season.

Experiment 39

The aim of this experiment was to examine onion-sugar-cane intercropping, the effect of different genotypes of sugar-cane and difference within row distances of onion cv. Lumbu hijou. There were four combinations of onion and sugar-cane and two sole sugar-cane combinations arranged in a Randomized Complete Block Design with four replicates. The intercropping treatments were combinations of two different genotypes of sugar-cane (A_i) (i.e. cv. PS-41 and cv. POJ-3016) and two different within row distances of onion (B_j) (i.e. 40 × 5cm and 40 × 10cm). The between row distance of sugar-cane was 100cm and the plot size was (10.0 × 7.0)m².

Experiment 40

This experiment was rather similar to experiment 39. There were also four intercropping treatments and two sole crops of sugar-cane, arranged in a Randomized Complete Block Design with four replicates. The intercropping treatments were combinations of the same two genotypes of sugar-cane as experiment 39 and two different within row distances of tomatoes (i.e. 100 × 50cm and 100 × 30cm). The plot size was also (10.0 × 7.0)m².

Experiment 41

Another experiment to examine the effect of intercropping systems on sugar-cane was conducted with a different secondary crop. There were also four treatments of intercropping systems arranged in a Randomized Complete Block design with four replicates. The intercropping treatments were combinations of two different genotypes of sugar-cane (A_i) as in experiment 39 and two different genotypes of maize (B_j) (i.e. cv. BC-2 and cv. Kretek). The planting distance of corn was 100 × 40cm. The plot size was (10.0 × 7.0)m².

Experiment 42

Another experiment of sugar-cane and corn intercrop was conducted to examine the effect of maize genotypes and planting distance of maize on intercropping systems. There were six treatments of maize and sugar-cane intercrop and one sole crop of sugar-cane arranged in a Randomized Complete Block Design with four replicates. The intercropping systems were combinations of two different genotypes of corn (A_i) (i.e. cv. BC-2 and cv. Kretek) and three different planting distances of maize (B_j) (i.e. 100 × 30cm, 100 × 40cm and 100 × 50cm). The between row distance of sugar-cane was the same as experiment 39 and the sugar-cane cv. POJ-3016 was used. The number of replications was four and the plot size was also (10.0 × 7.0)m².

Experiment 43

This experiment was also on maize and sugar-cane intercropping. There were ~~six~~ 8 treatments arranged in a Randomized Complete Block Design with four replicates. The treatments were combinations of two different genotypes of sugar-cane (A_i) (i.e. cv. PS-41 and cv. POJ-3016), two different row distances of sugar-cane (B_j) (i.e. 100cm and 110cm between rows) and planting systems (C_k) (i.e. either sole sugar-cane or intercropped with corn). The maize cv. BC2 with planting distance of 100 × 30cm was used in this experiment. The plot size was (8.0 × 6.0)m².

Experiment 44

Another type of experiment to examine the effect of between row distance and planting systems on sugar-cane and maize was conducted. The six treatments were combinations of three different between row distances of sugar-cane (A_i) (i.e. 100cm, 110cm and 115cm between rows) and systems of planting (B_j) (i.e. either sole sugar-cane or intercropped sugar-cane and corn). The maize cv. Kretek with planting distance of 100 × 40cm and the sugar-cane cv. POJ-3016 was used in this experiment. The design was a Randomized Complete Block with four replicates and the plot size was (10 × 6.0)m².

Experiment 45

This experiment was aimed at assessing the effect of the secondary crops on sugar-cane under intercropping. There were two treatments of intercropping systems (i.e. peanut and sugar-cane, upland rice and sugar-cane and one sole sugar-cane arranged in a Randomized Complete Block with seven replicates). The peanut cv. Gajah and the upland rice cv. IR-36 with 4 rows of peanut or upland rice between rows of sugar-cane were used in the experiment. The plot size was (50 × 10)m².

Experiment 46

This experiment was the same as experiment 45, but conducted at a different station. Experiment 45 was conducted in Pasuruan, experiment 47 in Jatiroto. The sugar-cane cv. BZ132 with 100cm between row distances was used in experiment 46. The plot size was also (50 × 10)m².

Experiment 47

This experiment was rather similar to experiment 45. There were three treatments of sugar-cane intercrop (i.e. sugar-cane and peanut, sugar-cane and mungbean, and sugar-cane and broad bean) and one sole sugar-cane arranged in a Randomized Complete Block with six replicates. The sugar-cane cv. BZ132 with 100cm between row distance and the peanut cv. Gajah, the mung-bean cv. Bhakti, and the broad bean cv. Pasito with 4 rows of these second crops between sugar-cane rows were used. The plot size was (10 × 5.0)m².

Experiment 48

The aim of this experiment was also to examine the effect of different types of secondary crops on sugar-cane intercropping systems. The four sugar-cane intercropping systems were soybean and sugar-cane; peanut and sugar-cane; mungbean and sugar-cane; broad bean and sugar-cane. There was also a control treatment, sole crop of sugar-cane. The sugar-cane cv. POJ-3016 was used with between row distance of 100cm. The soybean cv. Orba, peanut cv. Gajah, mungbean No. 129 and broad bean cv. Pasito were used in the experiment with one row of the second crop between rows of sugar-cane. The design was a Randomized Complete Block with six replicates. The plot size was $(6.0 \times 7.5)m^2$.

Experiment 49

This experiment was also designed to assess the effect of different secondary crops on sugar-cane under intercropping. There were six different secondary crops (i.e. peanut cv. Gajah, mungbea No. 129, soybean cv. Orba, white sesame, maize cv. Harapan and sweet potatoes cv. Tumpluk) intercropped with sugar-cane. The sugar-cane cv. POJ-3016 was used with 100cm between row distances. The design was also a Randomized Complete Block with four replicates. The plot size was $(20 \times 12)m^2$.

Experiment 50

This experiment was aimed at assessing the effect of nitrogen fertilizer on sugar-cane and corn intercropping systems. There were four treatments of sugar-cane and corn intercrop (as in table below) arranged in a Randomized Complete Block with six replicates.

a: Sugar-cane was fertilized at 7 and 37 days after germinating.
Corn without fertilizing.

b: Sugar-cane was fertilized as a.
Corn with fertilizing.

c: Sugar-cane was fertilized twice at 7 days after corn was harvested.
Corn with fertilizing.

d: Sugar-cane was fertilized three times at 7 days, 37 days and after corn was harvested.

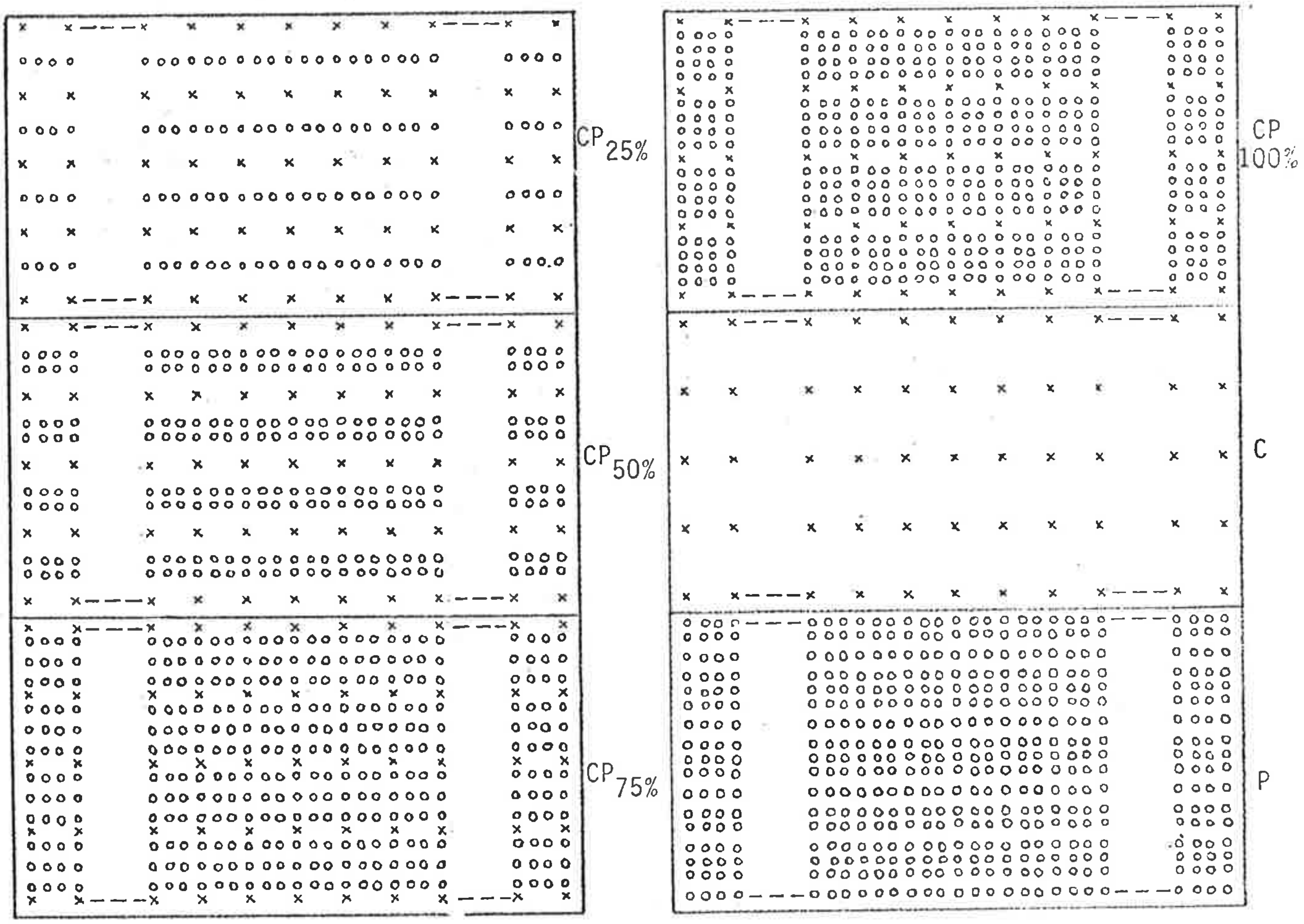
Corn without fertilizing.

The sugar-cane cv. POJ-3016 with 100cm between rows and corn cv. Kretek with planting distance of 100 × 30cm were used in this experiment. The plot size was $(7.5 \times 11)m^2$.

Experiment 51

This experiment was the same as experiment 50, but conducted at a different station. Experiment 50 was conducted in Pasuruan, this experiment in Jatiroto. The number of replications and plot size were also the same as experiment 50.

I	II	III	IV	V	VI
$CP_{100\%}$	$CP_{50\%}$	C	$CP_{25\%}$	$CP_{100\%}$	$CP_{50\%}$
$CP_{25\%}$	$CP_{100\%}$	$CP_{25\%}$	$CP_{50\%}$	C	$CP_{75\%}$
P	C	P	$CP_{100\%}$	$CP_{50\%}$	P
$CP_{50\%}$	$CP_{75\%}$	$CP_{50\%}$	P	$CP_{75\%}$	$CP_{25\%}$
C	$CP_{25\%}$	$CP_{100\%}$	$CP_{75\%}$	P	C
$CP_{75\%}$	P	$CP_{75\%}$	C	$CP_{25\%}$	$CP_{100\%}$



x = cassava
o = peanut

Fig. 3.2.1 Randomization scheme and the arrangement of crops in experiment 1. C = cassava , P = peanut.

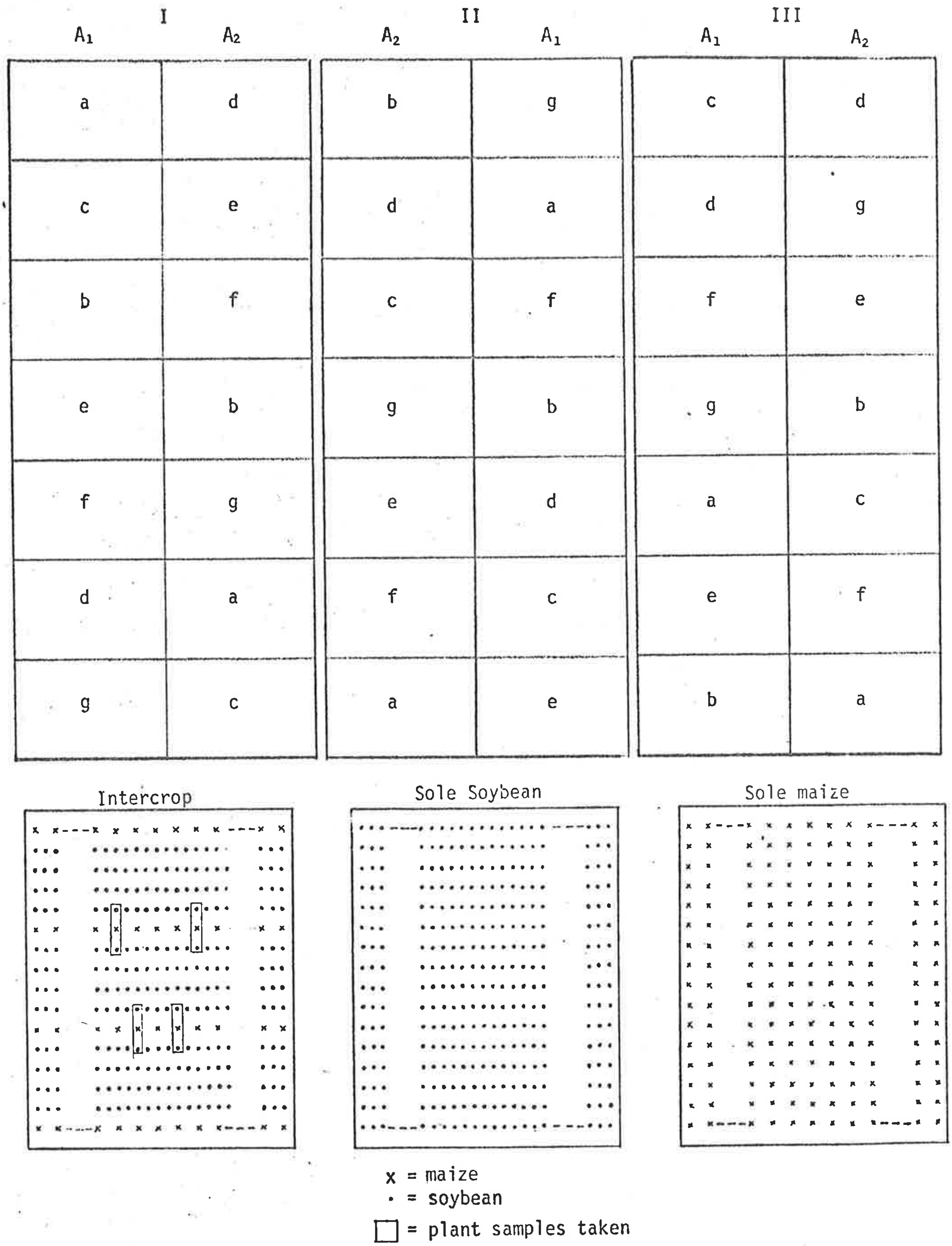


Fig. 3.2.2 Randomization scheme and the plant samples taken of experiment 9.

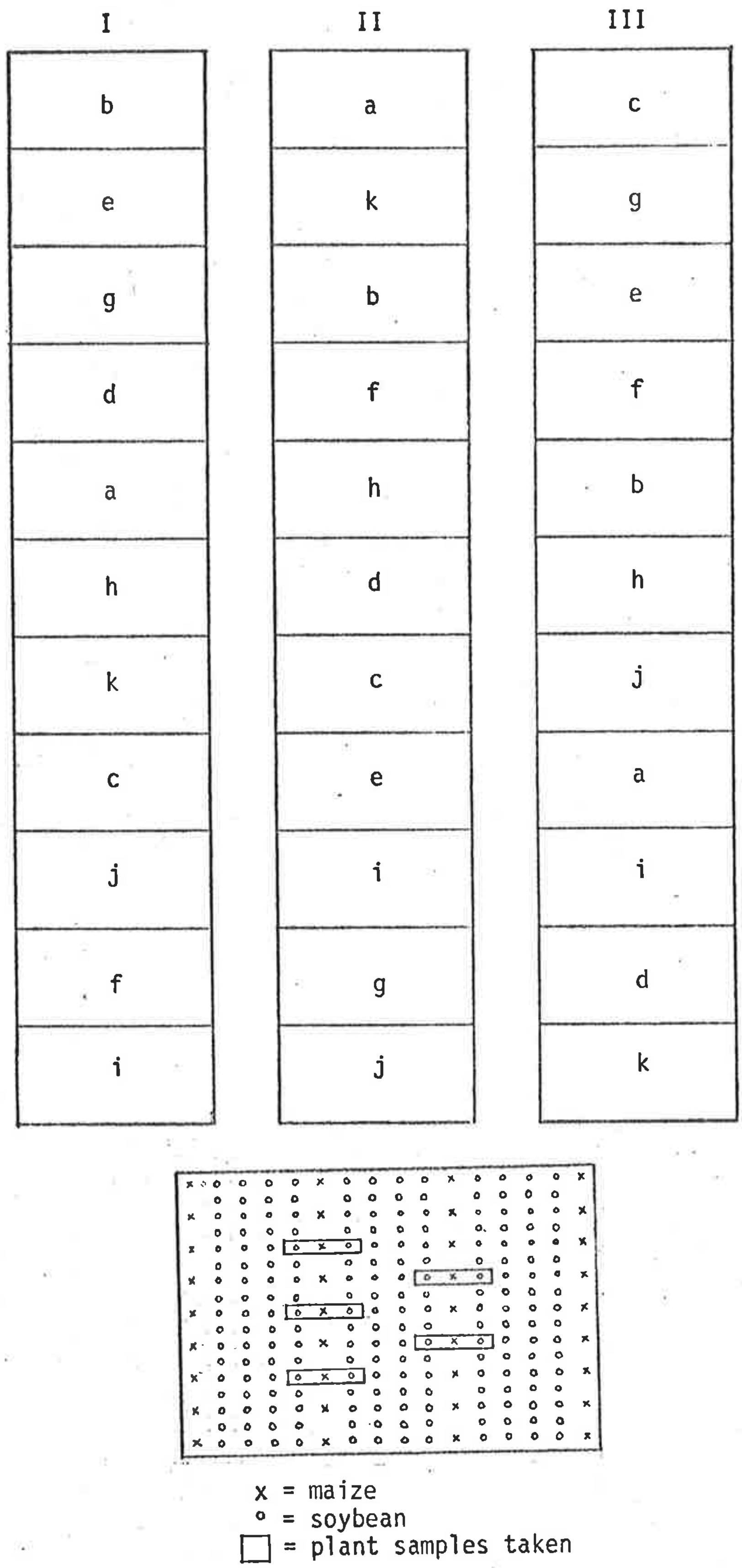


Fig. 3.2.3 Randomization scheme and the plant samples taken in experiment 29.

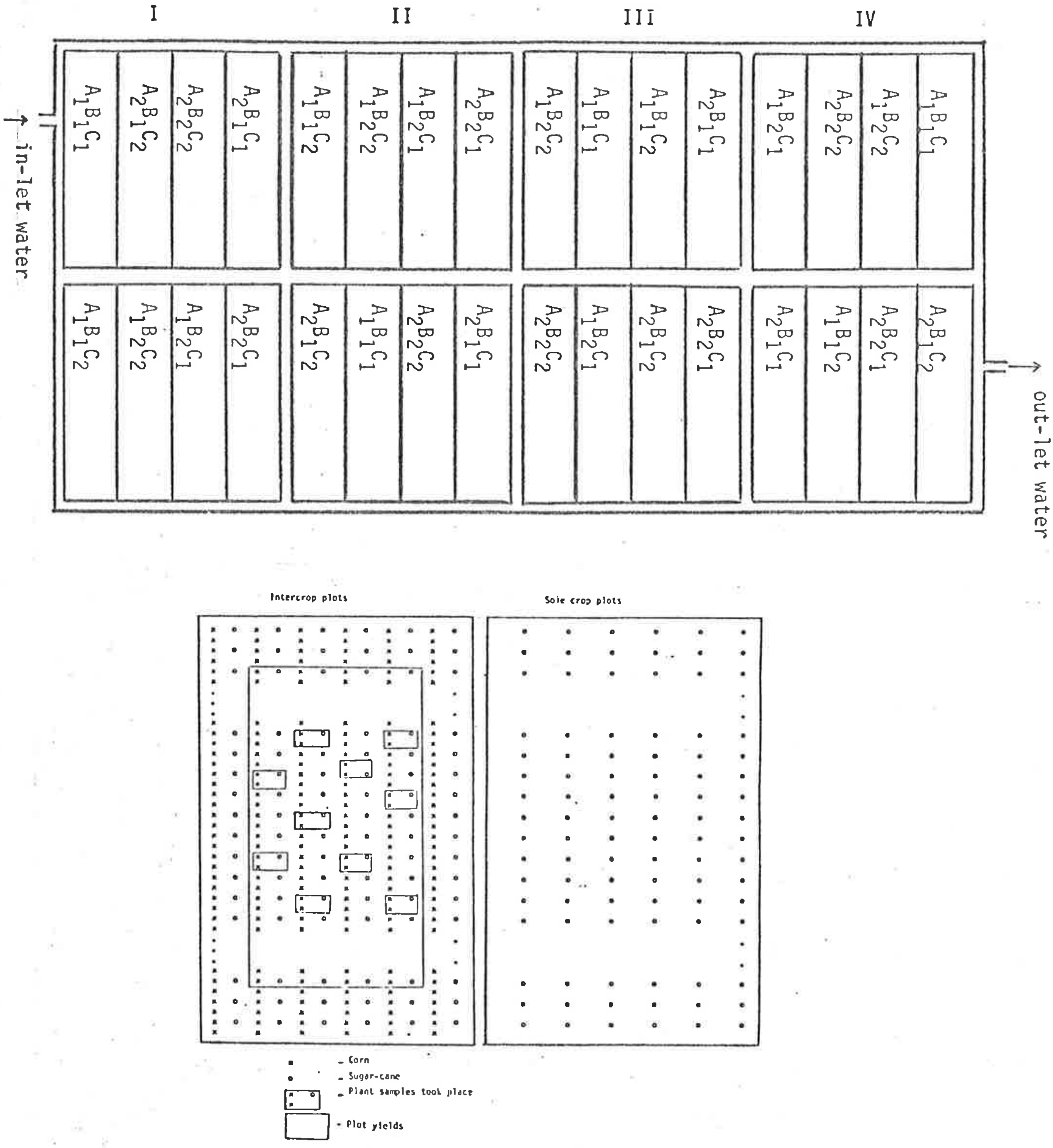


Fig. 3.2.4 Randomization scheme, the plant samples took place and plot yields area of experiment 43.

Since S_A and S_B have positive probability of being zero, a sum of Cauchy variables can arise. If S_A and S_B are known constants, $L_A + L_B$ has a univariate normal distribution if M_A and M_B have a bivariate normal distribution. When S_A and S_B are random variables, problems with Cauchy distributions may arise. For example, the outliers discussed on p. 66 below might arise from a Cauchy-like distribution.

IV. STATISTICAL ANALYSES FOR ASSESSING YIELD ADVANTAGES

IV.1 TESTING THE VALIDITY OF THE MODELS

IV.1.1 THE DISTRIBUTION AND HOMOGENEITY OF VARIANCE OF THE LER IN DIFFERENT STANDARDIZATIONS

1. INTRODUCTION

In using the LER (2.1.1.1) as the index of yield advantage or disadvantage, and comparing different intercrop mixture treatments (for the two component crops), various different philosophies have been debated for choosing S_A and S_B (Oyejola and Mead, 1982).

Three basic definitions of standardizing yields (i.e. either yield of each component genotype or average yield of all sole genotypes or yield of the best sole genotype) have been proposed by Huxley and Maingu (1978), Mead and Stern (1979) and Mead and Willey (1980). There is also a further complication, namely whether the standardization yield should be the same for the whole experiment, or should vary between blocks (Fisher, 1977, 1979).

Oyejola and Mead (1982) emphasized that although decisions about standardizing yield will always be influenced by the particular agronomic situations, there are also statistical reasons for choosing which S_A and S_B to use. It appears from the results of Marsaglia (1965) that the distribution of the ratio of two non-negative normal variables can take many different forms, ranging from unimodal symmetrical curves to bimodal positively skewed curves with extreme kurtosis. Ratkowsky (1983) also indicated that the distribution of the ratio of two normally distribution random variables is not itself a normally distributed random variable.

By using the combination of the three definitions of standardizing yields (i.e. yield of each component genotype, average yield of all sole genotypes and yield of the best sole genotype) and the two standardizations of yield (i.e. either vary between blocks or the same for all blocks); Oyejola and Mead (1982) examined the assumption of the analysis of variance that observations are normally distributed and the precision of comparisons arising from the analysis of variance of the Land Equivalent Ratio. A very important result from Oyejola and Mead's work is that the more divisors required by a standardization method, the greater are the doubts about the validity of the normal distribution assumption and the poorer is the precision of the treatments comparison. However, Fisher (1977, 1979) has argued that standardizing within each block to reduce the skewness of the distribution of LER's and standard errors as well. Wijesinha, Federer, Carvalho and de Aquino Portes (1982) also pointed out that the LERs are correlated in that one of the denominators is the same for a number of the LERs.

This study is aimed to re-examine in a range of relevant experiments on the non-normality and heterogeneity of variance of the Land Equivalent Ratio on the residuals.

2. STANDARDIZATIONS AND STATISTICAL METHODS

2.1 Standardization Methods

The calculation of an LER value essentially standardizes the two components of crop yields, but there may be several possible choices for this procedure (Mead and Willey, 1980). As Mead and Willey emphasized, the appropriate method of standardization will always be influenced on the form and objective of the experiment. A good example where a single standardizing sole crop yield would be agronomically valid is where treatments consist of different plant populations and spacing. Huxley and Maingu (1978) have pointed out that all intercrop yields should then be compared with the sole crop at its optimum population and spacing, therefore in that case intercropping should be compared with sole plots which are at maximum productivity in this respect.

There are other situations where it seems sensible to use more than one measure of sole crop yield. For example, when a treatment such as herbicide or fertilizer is not constantly available to the farmer, the use of more than one sole crop yield will indicate the relative advantages of intercropping that can be achieved for the different fertility levels (Mead and Riley, 1981).

Mead and Stern (1979) also argued that sole crop yield for standardizing intercropping yield in the calculation of the LER should be simply an estimate of average sole crop yield. A further necessary decision is whether the standardization yield should vary between blocks or be the same for the whole experiment. Fisher (1977, 1979) argued for standardization within each block, to reduce standard errors and also the skewness of the distribution of LERs, but Oyejola and Mead (1982) argued that the more divisors we use in standardizing LERs, the greater are the doubts about the validity of the normal distribution assumptions.

Therefore, in this study as in those of Pentilades (1979) (in Mead and Riley, 1981) and Oyejola and Mead (1982), six different standardizers of sole crop are reconsidered:

i) yield for corresponding sole crop treatment (L_1);

ii) yield for the average of all sole crop treatments (L_2);

iii) yield for the best sole crop treatments (L_3);

each with

a) same standardization for all blocks (L_{i1});

b) separate standardization in each block (L_{i2}).

These six methods of standardization are referred to hereafter as L_{11}, L_{21}, L_{31}, L_{12}, L_{22} and L_{32}.

2.2 Statistical Methods

To apply the analysis of variance, the experimenter must first make some assumptions about the data. He must assume that the population of observations within any area of study, A_i, is normally distributed with a mean, μ_i and a variance σ^2. A further assumption and one of the most important is that the residual variances of all observations are equal, and that all observations are independent of each other.

Most of the literature (Lindquist, 1953; Scheffé, 1959; Lindman, 1974 and Subrahmaniam et al., 1975) mentions that sampling distribution appropriate to the analysis of variance (i.e. the F-distribution) is remarkably insensitive to the form of distribution of criterion measures in the parent population, granting that the form is common to all treatments. Discrepancies significant at the 5% level are found only for the leptokurtic and rectangular distributions, and even there the absolute discrepancies are quite small (Lindquist, 1953). As pointed out by Scheffé (1959), however, though non-normality does not bias our point of estimates of parameters or of variance components, non-normality will in general invalidate the normal theory formulae for variance components, since these are based on theoretical distributions which distribute the mean squares for random effects as linear functions of χ^2 variables and such distributions may be bad approximations in the presence of non-zero kurtosis.

While studies of the robustness of the F-test have shown that the violations of normality has little effect on inferences about the means, violation of the requirements of independence or of equality of variances can have a serious effect on inferences about the means, especially for unequal numbers of observations (Scheffé, 1959; Brown and Forsythe, 1974). It was apparent from Norton's study (Lindquist, 1953) that marked heterogeneity of variance has a small but real effect on the form of the F-distribution. If one used the probabilities read from the normal F-table in interpreting the results of an experiment with this degree of heterogeneity, one might think one was making a test at the 5% level when it was actually at the 7% level. For this reason, a common practice in research using the analysis of variance has been to test the assumption of equality of variances before calculating F. If the result of the test is significant, the experimenter concludes that the F-test cannot be made, if the result is not significant the experimenter concludes that the F-test is justified. Of course, this amounts to accepting the null hypothesis of homogeneity of variance as true, and the appropriateness of accepting a null hypothesis, given significant statistical results, has long been a subject of debate.

In this study, however, there is a good background to test both non-normality and variance heterogeneity of data, since there are theoretical demonstrations cited above that the ratio of two normally distributed random variables is not itself necessarily a normally distributed random variable but can take many different forms, and since LER is the sum of the ratios of possibly Guassian variables.

2.2.1 Non-normality tests

In considering the effects of non-normality, one finds it convenient to use the measures g_1 of skewness and g_2 of kurtosis of distribution of random variable X. Skewness is essentially another name for asymmetry, i.e. one tail of the curve is drawn out more than the other. In such curves the mean, the mode and the median will not coincide. Curves are called skewed to the right or left, depending upon whether the right or left tails are drawn out. Deviations associated with kurtosis can be described as either leptokurtic (where $g_2 > 0$) or platykurtic (where $g_2 < 0$). Leptokurtosis arises if the distribution indicates the distribution is unusually flattened. To test the null hypothesis, that the distribution of a sample is normal, the coefficients of skewness and kurtosis have been used separately or combined. In combining g_1 and g_2, by assuming they are independent D'Agostino and Pearson (1973) proposed two "omnibus" tests. However, they withdrew those tests after Anscombe pointed out that while g_1 and g_2 were uncorrelated, they were not independent. There are also many other tests that are based on combining g_1 and g_2 (Bliss, 1967; Bowman and Shenton, 1975; Pearson et al., 1977).

Shapiro and Wilk (1965) proposed another test for non-normality, the W-statistic. This criterion basically compares the slopes for the regression of the ordered observations on the expected values of the order statistics, with the usual asymmetric sample sum of squares about the mean. Extensive empirical comparisons of W with other tests of non-normality using computer generated pseudo-random numbers indicated that W had good power properties against a wide range of alternative distributions and was therefore truly an "omnibus" test (Shapiro et al., 1968). Subsequently, other statistics of the W type, namely Y (D'Agostino, 1971), W' (Shapiro and Francia, 1972), r (Filliben, 1975) and $\tilde{W}'$ (Weisberg and Bingham, 1975) were developed and shown to have power properties broadly comparable with those of W.

In fact, there are still futher tests of normality in the literature. However, they have not been included in this study as previous work had shown them to be comparatively insensitive to deviations from normality (see Shapiro et al.). After searching through the literature, the power of the omnibus tests may be summarized as follows. For symmetrical platykurtic distributions ($g_1 = 0$, $g_2 < 3$) and for most skew distributions W is optimal (Pearson, et al., 1979), and is sometimes markedly more powerful than its nearest competitor. W', r and k^2 are all more powerful than W for symmetric, leptokurtic populations ($g_2 > 3$), though W seems little inferior for very long-tailed alternatives, e.g., $g_2 = 11$. W' and r (Filliben, 1975), W' and $\tilde{W}'$ (Weisberg and Bingham, 1975) appear to have similar powers.

Thus, there is no one test of normality sensitive to all types of departure from normality. In some situations, it may be possible to specify the way in which data are likely to depart from normality and we can use a test especially sensitive to the expected type of departure. However, if we do not have any prior idea of the expected direction of the departure from normality we need an omnibus test sensitive as far as possible to any form of departure (Pearson et al., 1977).

Federer (in discussion of Mead and Riley, 1981) pointed out that we have no real knowledge of the distributional properties of the Land Equivalent Ratio (LER). Therefore, in this study I consider g_1, g_2 and the combination of g_1 and g_2 and W tests for detecting non-normality of LER. Although the use of g_1, g_2 and combination of g_1 and g_2 (Bliss, 1967) would be dubious, unless the number of samples is large enough, I still continue to use them as also I consider the W test. Royston (1982a) has extended the W test up to sample size $n \leq 2000$ and given an algorithm for calculating W and its significance level by using algorithm AS66 (Hill, 1973); AS177 (Royston, 1982c) and AS111 (Beasley and Springer, 1977). Therefore, there are no problems for sample size $n > 50$ and computation of the W statistic. I have omitted one misprint in the W algorithm of Royston (1982b); Y_{Bar} - Exp (Poly (WE, 6, A11)).

Mead (1983) argued that it is not sensible to include sole crop plots with mixed crop plots, in analysing LER. It also could be argued that if the aim of the experiment is to compare planting systems (i.e. either monocrop or intercrop) so that the sole crops function as treatments not as control plots, then we may include sole crop with mixed crop plots. As Willey (1979) also emphasized, by using LER whatever the degree of crop yield, we can put all the results on a relative and directly comparable basis. Therefore, in this study I include sole crop plots with mixed crop plots for the experiments that considered sole crop plots as treatments and exclude sole crop plots with mixed crop plots for the experiments that considered sole crop plots as control treatments.

Tests considered:

a.1. The Coefficient of Skewness

The Coefficient of Skewness is estimated by the statistics g_1, given by the third central moment to the cube of the standard deviation, i.e.

$$g_1 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^3}{n\left[\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}\right]^{3/2}} \qquad (4.1.1.1)$$

where $x_1, x_2, \ldots, x_n$ is a sample of n observations. The significant of g_1 may be tested since the statistic

$$tg_1 = \frac{g_1}{Sg_1}$$

where

$$Sg_1 = \sqrt{\frac{6n(n-1)}{(n-2)(n+1)(n+3)}} \qquad (4.1.1.2)$$

is approximately normally distributed when the null hypothesis of zero skewness is true. The alternative hypothesis is two-tailed.

a.2. The Coefficient of Kurtosis

The Coefficient of Kurtosis is estimated by the statistic g , which is three less than the ratio of the fourth central moment to the fourth power of the standard deviation,

i.e. $$g_2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^4}{n\left[\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}\right]^2} - 3 \qquad (4.1.1.3)$$

The equivalent null and alternate hypotheses as in skewness apply and the approximately normally distributed statistic (under H_0)

$$tg_2 = \frac{g_2}{Sg_2}$$

where

$$Sg_2 = \sqrt{\frac{24(N - 1)^2}{(n - 3)(n - 2)(n + 3)(n + 5)}} \qquad (4.1.1.4)$$

(These standard errors for skewness and kurtosis coefficient are approximations, but their accuracy is considered to be sufficient for the present circumstances (Bliss, 1967)).

a.3. Joint Test of Skewness and Kurtosis

If the coefficent of skewness is significant and the kurtosis is not or vice versa, their combined evidence determines whether the sample is significantly non-normal (Bliss, 1967). To test the null hypothesis, we compute

$$\frac{g_1^2}{V(g_1)} + \frac{g_2^2}{V(g_2)} \qquad (4.1.1.5)$$

and compare it with χ^2 with 2 degrees of freedom, and read the required probability from the χ^2 table.

b.1. The W test statistic

Let $m' = (m_1, m_2, \ldots, m_n)$ denote the vector of expected values of standard normal order statistics, and let $v = (\nu_{ij})$ be the corresponding $n \times n$ covariance matrix. That is, if $x_1 \leq x_2 \leq \ldots \leq x_n$ denotes an ordered random sample of size n from a standard normal distribution ($\mu = 0$, $\sigma = 1$), then

$$E(x_i) = m_i (i = 1, 2, \ldots n),$$

and

$$Cov(x_i, x_j) = \nu_{ij} (i, j = 1, 2, \ldots, n).$$

Let $\underset{\sim}{y}' = (y_1, y_2, \ldots, y_n)$ denote the ordered vector of a random sample.

It is desired to derive a test for the composite hypotheses that $\{y_i\}$ is a sample from a normal distribution with unknown mean μ and unknown variance σ^2. If $\{y_i\}$ is a normal sample, then y_i may be expressed as

$$y_i = \mu + \sigma^2 x_i \quad (i = 1, 2, \ldots, n). \qquad (4.1.1.6)$$

The W test statistic is then defined as

$$W = \frac{\left(\sum_{i=1}^{n} a_i y_i\right)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \qquad (4.1.1.7)$$

where

$$\underset{\sim}{a}' = (a_1, a_2, \ldots, a_n) = \frac{m'v^{-1}}{(m'v^{-1})(v^{-1}m)^{\frac{1}{2}}}$$

The coefficients $\{a_i\}$ are the normalized "best linear unbiassed" coefficients tabulated for $n \leqq 20$ by Sarhan and Greenberg (1956). Approximations were developed by Shapiro and Wilk (1965) for calculating coefficients for using the W test up to sample size $n \leqq 50$ and further extended by Royston (1982a) up to $n \leqq 2000$. Royston also used the approximation method for getting $\{a_i\}$ coefficients. By definition, $\underset{\sim}{a}$ has the property $\underset{\sim}{a}'\underset{\sim}{a} = \underset{\approx}{I}$. Let $a^* = m'v^{-1}$, approximations $\hat{a}^*$ for a^* are

$$\hat{a}^*_i = \begin{cases} 2m_i , & i = 2, 3, \ldots, n-1, \\ \left(\dfrac{\hat{a}_1^{\,2}}{1-2\hat{a}_1^{\,2}} \sum_2^{n-1} \hat{a}^{*2}\right) & i = 1,\ i = n. \end{cases}$$

where

$$\hat{a}_1^2 = \hat{a}_n^2 = \begin{cases} g(n-1) & n \leqq 20, \\ g(n) & n > 20. \end{cases}$$

and

$$g(n) = \frac{\Gamma(\frac{1}{2}[n+1])}{\sqrt{2}\Gamma(\frac{1}{2}n+1)} .$$

Using Sterling's formulae, g(n) may be approximated and simplified:

$$g(n) = \left[\frac{6n+7}{6n+13}\right] \left\{\frac{\exp(1)}{n+2} \left[\frac{n+1}{n+2}\right]^{n-1}\right\} \qquad (4.1.1.9)$$

By using the formulae (4.1.1.8) and (4.1.1.9), Royston extends the values of a_i and the W statistic is also calculated using those formulae.

2.2.2. The precision of comparisons of LERs

Mead (1983) suggested considering the precision of comparisons of the six standardizations discussed above. The precision of comparison arising from the analysis of variance is examined by considering the residual sum of squares of the analyses, and the standard errors of treatment differences. As Oyejola and Mead (1982) also indicated, a simple comparison of the values for the six different standardizations is not valid for either of those two measures. Because the standardizations use divisors of consistently different magnitudes, in calculating the LERs analysis, the absolute size of LERs is different for the different standardizations, which will affect both sums of squares and standard errors. It is therefore appropriate to consider the standard error as a percentage of the overall mean (the coefficient of variation), and the residual SS as a proportion of the total SS; however, some standardizations (L_{11}, L_{21} and L_{31}) attempt to eliminate block differences, and the total to which it is relevant to compare the residual SS is the total SS after eliminating block variation (Oyejola and Mead, 1982).

Since the correct value of LER for experimental data is always unknown and no absolute measure of bias is possible, we do not consider this measure and only examine the distribution and precision of comparisons of the six standardizations.

2.2.3. Homogeneity of variance tests

The most frequently used test for homogeneity of variance is Bartlett's (1937) test, originally introduced by Neyman and Pearson (1937). However, although it is unbiassed (Pitman, 1939) and is locally most powerful when the underlying distribution is normal (Ghosh, 1972; Shukla, 1982), it is well known to be extremely sensitive to departues from normality (Box, 1953). For this reason, many others tests have been introduced (Box, 1953; Gnanadesikan, 1959; Krishnaiah, 1965; Miller, 1968, Layard, 1973 and Brown and Forsythe, 1974). While some of these tests are more robust to certain departures from normality, few of them are very powerful. Layard (1973) studied the power and robustness of homogeneity of variance tests. He concluded that a simple χ^2 test (Layard's test) and a test based on the jack-knife procedure are reasonably robust for moderately small samples, are more powerful than Box's grouping test and perform similarly to Bartlett's test in the normal case. From this view, Layard recommended a simple χ^2 test for cases of computation. Layard also suggested that a similar modification of Bartlett's would improve the robustness of the test, although he did not include it in his study. From the study of Keselman et al. (1979), it appears that the current tests for variance heterogeneity are either sensitive to non-normality or, if robust, lacking in power.

For those reasons, I consider Bartlett's test, Bartlett's test as modified by Box and Layard's test as comparisons for testing the heterogeneity of variance. Shukla (1975, 1982) pointed out that in two-way classifications there are situations where variances may differ between columns or rows but they remain the same within the same column or row. Kanji (1975) also indicated that in the two-way layout between column test, the power value is greatly affected by the inequality of column variances, but only slightly affected by the serially correlated within-rows error variable. The result of Shukla (1982) also shows that Bartlett's test gives satisfactory results even for a very small number of observations in each row or column (i.e. $n \geqq 3$). As not all experiments can be fully analysed in terms of the LER, so only the experiments that are appropriate will be considered.

Test considered

Let the observations y_{ij} be arranged in p rows and t columns ($i = 1, 2, \ldots, p$; $j = 1, 2, \ldots, t$). An appropriate model relating the y_{ij} to unknown parameters μ_i α_i, β_j is considered to be

$$y_{ij} = \mu + \alpha_i + \beta_j + e_{ij} \qquad (4.1.1.10)$$

where $e_{ij} \sim N(0, \sigma^2)$.

In this study, we shall proceed with the test of equality of columns or rows variance on residuals after fitting rows or column effects separately and assuming no interaction effect. The hypothesis to be tested is H_0: $\sigma_1^2 = \sigma_1^2 = \ldots = \sigma_p^2 = \sigma^2$, versus the alternative that not all σ_i^2 are equal (i.e. for rows effect). The same method also applies to the columns effect. Although the tests are proposed to the random models, those tests also apply to the residual after fitting columns or rows effects separately (Appendix C). The following tests were included in this study.

(1) Bartlett's test

In general, we consider k samples with variances, $S_i^2 = 1, \ldots, k$ and sample sizes n_i, $i = 1, \ldots, k$. If the residuals after fitting rows or column effects can be assumed to be normal, Bartlett's test is a modification of the Neyman-Pearson likelihood ratio test, and is

$$B = -\frac{1}{c}\sum_{i=1}^{k}(n_i - 1)\ln\left(\frac{S_i}{\bar{S}}\right) \sim \chi^2_{k-1} \tag{4.1.1.11}$$

where

$$\bar{S}^2 = \frac{\sum_{i=1}^{k}(n_i - 1)S_i^2}{\sum_{i=1}^{k}(n_i - 1)}$$

$$c = 1 + \frac{1}{3(k-1)}\left[\sum_{i=1}^{k}\left(\frac{1}{n_i - 1}\right) - \frac{1}{\sum_{i=1}^{k}(n_i - 1)}\right].$$

(2) Layard's test

Let A denote the asymptotic test statistic introduced by Layard (1973), namely

$$A = \frac{\sum_{i=1}^{k}(n_i - 1)\left[\ln S_i^2 - \frac{\sum_{i=1}^{k}(n_i - 1)\ln S_i^2}{\sum_{i=1}^{k}(n_i - 1)}\right] \sim \chi^2_{k-1}}{(2 + (1 - \frac{k}{N})g_2} \tag{4.1.1.12}$$

where $N = \sum_{i=1}^{k} n_i$.

In estimating the amount of kurtosis (g_2) of a distribution, Layard (1973) found that the resultant bias from using the weighted average of sample kurtosis estimates can be reduced by using

$$g_2 = \frac{N\sum_{i=1}^{k}\sum_{j=1}^{n}(y_{ij} - \bar{y}_i)^4}{\sum_{i=1}^{k}\sum_{j=1}^{n}(y_{ij} - \bar{y}_i)^2)^2} \tag{4.1.1.13}$$

for a normal population.

(3) Modified Bartlett's test

As pointed out by Box (1953), when $g_2 = 0$, Bartlett's test criterion approximates to χ^2_{k-1}, but when $g_2 \neq 0$, the relevant distribution is $(1 + \frac{1}{2}g_2)\chi^2_{k-1}$. Thus, a simple modification, $B/(1 + \frac{1}{2}g_2)$ can provide a robust test (Layard, 1973) and g_2 is defined as in 2.

3. RESULTS

The distribution and the precision of LER

As can be seen in Section III.2, not all experiments have sole crop treatments, therefore only the appropriate experiments will be used to illustrate normality and homogeneity of variance in the residuals of six LER standardizations. First, we examine the intercropping treatments (i.e. after excluding sole crop treatments). Detailed investigation was carried out using experiments 10 and 11 (i.e. the same experiment but different in season), experiment 12 and 13, which differed only in the secondary crop and experiment 14, which differed only in the season from experiment 13. Experiment 10 involved intercropped corn and soybean and experiment 13, corn and mungbean intercrop.

Table 4.1.1.1 lists the results of non-normality tests based on the residuals after fitting block and treatment effects for six standardizations. First, we note from Table 4.1.1.1 the coefficient of skewness for average block standardization (i.e. L_{11}, L_{21} and L_{31}). Except in experiment 11, the coefficients of skewness of L_{21} and L_{31} are smaller than L_{11}, but more variable in each block standardization (i.e. L_{12}, L_{22} and L_{32}). By this result, it seems that L_{21} and L_{31} are closer to normal than L_{11} for average block standardization and there is no real difference between L_{12}, L_{22} and L_{32} standardizations. The kurtosis coefficient, however, shows different results. There were no certain patterns relating to L_{11}, L_{21} and L_{31} or L_{12}, L_{22} and L_{32}. The results are more variable between each block standardization or average block standardizations. In fact, in experiment 14, there were substantial reductions both for coefficient of skewness and kurtosis by average block standardization. The range of skewness coefficient for six standardizations was very low (i.e. -0.035 to 0.380) except for experiment 14. Non-normality detected by skewness and kurtosis coefficients appeared only in experiment 14 by each block standardization (i.e. L_{12}, L_{22} and L_{32}).

Comparison between the coefficients of skewness and kurtosis suggests that they are not highly correlated so that the joint skewness and kurtosis test is of interest. Again, non-normality appears in experiment 14 with each block standardization and in experiment 12 with L_{12} standardization. Inspection of the W test, however, suggests that only L_{12} of experiment 14 is non-normal. From these results, the distributions of the residuals of six LERs standardizations are still fairly normal. There were no real differences between each block standardization or average block standardization or between each sole treatment, average sole treatment and maximum sole treatment standardization themselves, though with the average block standardization of experiment 14, we get quite substantial reductions of both coefficient of skewness and kurtosis, a reduction which also occurred with L_{21} and L_{31} standardizations.

The coefficient of variation and the percentage of sums of squares of residuals can be seen in Table 4.1.1.2. Except for L_{12} standardizations of experiment 14, the coefficient of variation was quite small. All the coefficients of variation for all six LER values were smaller than 20%, except for L_{12} of experiment 14. Inspection of this variable shows that there is no consistent relationship between each block standardization with average block standardization or between each sole treatment, average sole treatment or maximum sole treatment standardization. The percentage of sums of squares of residuals supports the previous results. The percentage of sums of squares or residuals is more variable between those six standardizations. Again, there was also no certain trend between average block standardizations.

These results can also be seen for all data sets, including the experiments that have just been discussed. Coefficients of skewness and kurtosis for six standardization methods are summarized in Table 4.1.1.3. Considering, first, the coefficient of skewness for all six LER values, except for experiment 7, the coefficient of skewness for all six LER values was quite small. The pattern of the results showed the same characteristics as for the five experiments that have just been discussed. Inspection of the kurtosis coefficient showed the same pattern as the coefficient of skewness. Again, neither each block standardization nor average block standardization nor between each sole treatment, nor average treatment nor maximum sole treatment standardization was clearly best. Non-normality tests based on these two coefficients showed that all six standardization methods left approximately normal values for all experiments. Inspection on the joint skewness and kurtosis coefficient tests and the W test (Table 4.1.1.4) showed also the same results. For the W test, except for experiment 7, the six standardization methods yield values still close to normal. Comparing the combined skewness and kurtosis test and the W test, it seems that the W test was not sensitive for kurtosis coefficient of > 1.70.

The coefficient of variation and the percentage of sums of squares of residuals of six LER values for all data sets as shown in Table 4.1.1.5. The coefficients of variation were quite small for all six standardization methods. The pattern of the coefficient of variation between average block standardization and each block standardization was variable.

The same pattern was also shown between each sole treatment, average sole treatment and maximum sole treatment standardization. Examining the percentage of sums of squares of residuals yields the same results as the coefficient of variation. Again, there was no real discrimination between the six standardization methods.

Let us now examine the experiments where the function of sole crop is treatments not as control plots, so that we may include sole crop plots with mixed crop plots. It appears that if we include the sole crop and we analyse by L_{12}, then the data are not usuable as all sole crop treatments have the same values (i.e. unity), therefore in this study we only consider the average block standardization (i.e. L_{11}, L_{21} and L_{31}). Non-normality tests on the residuals of LER values of average block standardization including sole crop treatments are summarized in Table 4.1.1.6.

We note from that table that the ranges of the coefficient of skewness for L_{11}, L_{21} and L_{31} are 0.00 to 2.502, 0.00 to -0.621, and 0.00 to -0.488 respectively. The ranges of the kurtosis coefficient for L_{11}, L_{21} and L_{31} are -0.098 to 13.965, 0.128 to 1.375 and 0.058 to 1.079. In fact, the range of either the coefficient of skewness or kurtosis for L_{11} is wider than L_{21} or L_{31} and quite similar for L_{21} and L_{31}. The coefficient of skewness and kurtosis for L_{11} are more significant than those for L_{21} and L_{31}. Inspection on the joint skewness and kurtosis test and the W test showed the same results. The L_{11} standardization was more often significant than L_{21} or L_{31}. This means that standardization by L_{21} or L_{31} yields fairly Gaussian results. However, the results of the coefficient of variation and the percentage of sums of squares of residuals were more variable between those three standardizations. In fact, the coefficients of variation of these three LER values are still quite small.

Considering the previous results (i.e. without sole crop plots) and including sole crop plots, the distributions for the latter case are more non-normal, especially for L_{11} standardizations. Comparing the intercropping treatments, however, except for experiments 7 and 14, the distribution of all six LERs was quite normal and there was again no real discrimination between those six LERs.

Homogeneity of Variance

As mentioned earlier, for experiments with two-way layout we shall proceed to test the equality of columns or row variances on residuals after fitting columns or rows effects separately. To examine more details of homogeneity of variance on residuals after fitting treatment and block effects, we consider plotting residuals against fitted values of experiment 10 and 11 and experiment 7 and 14, that showed non-normality of LER.

In Figures 4.1.1.1 to 4.1.1.4, residuals after fitting the appropriate model for experiment 10 and 11 have been plotted against fitted values. Clearly all the figures contain important information about the dispersion of residuals.

Let us examine, first the six standardization methods of experiment 10 (Figs. 4.1.1.1 and 4.1.1.2). From these figures, it appears that the dispersion of residuals of those six standardizations was satisfactorily homogeneous. Furthermore, there was no consistent pattern of dispersion of residuals between six standardizations and it could even be said that the dispersion of residuals of the six standardizations was quite similar, the difference, of course, lying only in the degree of clustering between each point of each treatment.

The results of experiment 11 (Figs. 4.1.1.3 and 4.1.1.4) showed the same pattern. Between each block and average block standardization or with each block and average block standardization yield quite similar results. Again, between six standardization methods there was no clear patterns in the dispersion of residuals. Furthermore, the dispersion of residuals of those six standardization methods appeared quite homogeneous. From these two experiments, it appears that the dispersion of residuals of LER values was quite homogeneous and there was no method clearly better than all others.

Experiments 7 and 14 showed discrepancies from the other experiments in their distribution of LER, so we also examine these in more detail by plotting residuals against fitted values (Figs. 4.1.1.5 and 4.1.1.6). From these two figures, it appears that the variances of L_{12} of experiments 7 and 14 increase with the mean values. In other words, the variances of these two experiments with L_{12} standardization were heterogeneous. In addition, there are outliers in these two figures. It seems that these outliers affected the fit to the models both in their distributions and homogeneity of variance of LER. By having the right standardization (i.e. L_{32}) in the case of experiment 7 (Fig. 4.1.1.7), and L_{21} or L_{31} standardizations of experiment 14 (Fig. 4.1.1.8), the outliers could be removed. Again, there was no standardizations that would guarantee giving satisfactory results when there were outliers in the data.

Clearly, assessing of the dispersion of residuals by plotting of residuals against fitted values demands much space to display results if many experiments must be examined. Therefore, for all data sets including those experiments that have just been discussed, the examination of homogeneity of variance will be assessed by the methods that have been described earlier.

Table 4.1.1.8 lists the results of homogeneity of variance tests on residuals of LER values of six standardizations of intercropping treatments for one-way layout. From this table, it appears that most of the LERs of experiment 7 have heterogeneous variance according to Barlett's test or Layard's test. By returning to the distribution of LER, it appears that experiment 7 was non-normal in most LER standardizations, so that the appropriate test was either Layard's or Bartlett's modified test. Nevertheless, the results showed that all the six standardization methods yielded homogeneous variances for all experiments except experiment 7. The same result was seen in the two-way layout experiments (Table 4.1.1.9, 4.1.1.10 and 4.1.1.11). According to Barlett's tests only the variances of L_{12} of experiment 14 for the first and second factors are heterogeneous (Table 4.1.1.10). Bartlett's modified test or Layard's test detected heterogeneity for L_{11}, L_{12} and L_{32} of the second factor of experiment 14 and also for L_{21} and L_{31} of the second factor of experiment 19 (Table 4.1.1.10 and 4.1.1.11). Considering Tables 8 to 11 together, one could conclude that most of the variances of six LER values were quite homogeneous. The two experiments that showed discrepancies have been detected earlier primarily due to outliers. The heterogeneity following L_{21} and L_{31} standardizations of experiment 19 could result from the interaction between the first and second factor (see Section IV.2, Table 4.1.17).

As I noted earlier, if sole crops are treatments in a given experiment, then we may include those plots with mixed plots to examine the effect of planting systems (i.e. either sole crop or intercrop). In examining homogeneity of variance of LER in experiments including sole crop, we only consider the average block standardization. The one-way layout experiments will be assessed by plotting residuals against fitted values and for experiments with factorial structure will be assessed by the methods that have been described earlier.

Figures 4.1.1.9, 4.1.1.10 and 4.1.1.11 show the dispersion of residuals of three LERs of experiments 6, 7 and 17. From these figures, apart from L_{21} and L_{31} of experiment 6, the variances of the three LERs of those three experiments were quite homogeneous. Examining these figures more precisely, most of them showed two different groups in the plots. These can be explained as being due to including the sole crop treatments in the model, so the two different groups are sole crop treatments and intercrop treatments. The other results for experiments with factorial structure appear in Table 12. It appears that most of the variances of planting systems were heterogeneous and also some of the second and third factor variances were made heterogeneous by including sole crop treatments. Furthermore, the variances of L_{11} standardized values were much more heterogeneous than L_{21} or L_{31} standardization.

4. DISCUSSION AND SUMMARY

Let us consider, first, differences between the intercropping treatments (i.e. after excluding sole crop treatments). From this study, it appears (Table 4.1.1.3) that the coefficient of skewness of residuals for six standardizations was quite small, except for some LERs of experiments 7 and 14. In fact, most of the values of the coefficient of skewness were smaller than 0.50 and there were even two experiments with skewness coefficients precisely zero. The coefficient of kurtosis test showed the same result, except that quite a few of the LERs showed approximate rectangular distributions (i.e. $g_2 \geqq 1.20$) or bimodal distributions (i.e. $g_2 \geqq 2.00$). From those two tests the residuals of all six LERs were quite normal, except in experiments 7 and 14. In fact, there were no consistent patterns for skewness and kurtosis coefficient across the six LERs. Examining Table 4 supports the previous result: the distribution of residuals of most of the six LERs was quite close to gaussian, with L_{21} and L_{31} all normal from 19 experiments. By comparing the two tests (i.e. combined skewness and kurtosis and the W test), it seems that W was slightly poorer in detecting non-normality in certain circumstances. This result would be expected from the demonstration by Pearson and Hartley (1976) that the W test was poorer than the coefficient of kurtosis in the case of the uniform distribution with $3.0 \geqq g_2 \geqq 1.8$.

As seen in the Figures ~~13~~ 4.1.1.5 and ~~14~~ 4.1.1.6, experiments 7 and 14 includ~~ing~~e outliers, so they showed discrepancies from the other experiments. From this study, it can be concluded that the distribution of residuals of all six LERs may be assumed Gaussian, provided that there are no outliers in the data. Most of the studies of the ratio of the two normal variables (Filler, 1932; Marsaglia, 1965; Hinkley, 1969 and Ratkowsky, 1983) were concerned with the distribution of this ratio in the case of a linear model incorporating random variables.

Here we have been concerned with the parametric model, and the residuals of all six LERs were indeed quite normal. The result of Gentleman (1975) supports this; she showed that, in the null cases (no outliers), residuals do behave much like a normal random variable. Gentleman (1975) and Miyashita and Newbold (1983) also indicated that the existence of one or two outlying observations in a sample can badly distort the summary indicators and analyses.

The choice of standardization between average block standardization and each block standardization or between each sole crop, average sole crop and maximum sole crop treatment standardization is difficult to summarize. As the previous studies (Fieller, 1932; Hinkley, 1969 and Ratkowsky, 1983) showed, the distribution of the ratio of two normal variables is approximately normal when the coefficient of variation of the denominator variate (CV_2) is close to zero or the correlation (ρ) between numerator and denominator is highly positive. Ratkowsky (1983) also showed that for $CV_2 \leq 20.00\%$ the normality of the ratio of two normal variables is more closely approached when numerators and denominators show a high positive correlation than when they are uncorrelated. The other results from Ratkowsky's study was that normality is not approached when numerator and denominator have a high negative correlation ($\rho = -0.90$). Shanmugalingham (1982) showed that the limiting value of coefficient of variation of numerator (CV_1) and correlation of numerator and denominator (ρ). He showed that (i) there is a symmetrical distribution of the ratio occurring when $\rho = CV_2/CV_1$ (ii) it is skewed to the left when $\rho > CV_2/CV_1$.

From these results, it is not a simple matter to choose the appropriate standardization for the ratio of the two normal variables. For example, different results were obtained by Fisher (1977, 1979) and Oyejola and Mead (1982) who considered skewness and kurtosis coefficient tests for testing normality of those six standardization methods. In this study, we re-examine these different results by considering not only coefficient of skewness and kurtosis but also joint of skewness and kurtosis and the W test. The results show that for the parametric model, the distribution of all six standardizations was indeed quite normal, as long as there were no outliers in the data. This result was also supported by the fact that the coefficient of variation of those six standardizations was quite small, except for experiments 7 and 14.

The results of the homogeneity of variance tests are also worthy of note. Except for experiments 7 and 14, the variance of rows or column residuals in most experiments of six standardizations, was quite homogeneous. Again, as appears in Figures 4.1.1.1 and 4.1.1.4, and Table 4.1.1.8 to 4.1.1.12, there was no consistent pattern of homogeneity of variance between those six standardizations and of course most of the variances were homogeneous.

Including sole crop treatments in the models distorted the behaviour of residuals both as regards normality and homogeneity of variance. It seems that the distortion in the models arose from the two patterns of groups (i.e. sole crop and intercrop treatments). If we return to the two experiments that present outliers, it could be that some sole crop treatments behave as outliers in the model. Therefore, in this situation we should be extremely careful in interpreting the results of intercropping experiments in terms of the Land Equivalent Ratio.

Let us now turn to experiment 7 and 14 again, as in the previous case, (i.e. after excluding sole crop treatments). The presence of outliers in those experiments could be the result of inclusion of zero N fertilizer treatments as a level of N fertilizer treatments (i.e. in experiment 7) and the inclusion of local genotypes of soybean within improved genotypes of soybean. Those two treatments from those two experiments yield much lower than the other treatments in each experiment. As Miyashita and Newbold (1983) emphasized, in analysing data when outliers are suspected, it would be desirable to try to account simultaneously for the possibilities of outliers and non-normal errors. The recommendation of Shanmugalingham (1982) and Carrol (1983), inter alios, may be taken as the use of either log transformation or robust methods for outliers to stabilize the variance and induce normality.

From this study, the distribution of residuals of six standardizations of most experiments was quite normal and the variances were quite homogeneous. Although there was no consistent pattern between those six methods, I recommend the use of either L_{21} or L_{31} (i.e. the average sole crop or the maximum sole crop standardization from the average block standardization) for ease of calculation and reliability of comparison between the intercrop treatments (see Section IV.2).

TABLE 4.1.1.1 Non-normality tests on residuals of LER values for six standardizations of intercropping treatments.

No. of Expt.	Coefficient of skewness L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}	Coefficient of kurtosis L_{11}	L_{21}	L_{31}	L_{12}	L_{12}	L_{32}
10	-0.188	-0.186	-0.184	0.089	-0.163	-0.166	-0.864	-0.841	-0.845	-0.783	-0.886	-0.873
11	0.060	0.157	-0.129	0.466	-0.118	-0.119	0.206	0.506	0.505	-0.039	-0.395	0.700
12	0.243	0.215	0.146	0.075	0.246	0.178	0.806	0.778	0.735	1.734	0.818	0.739
13	0.380	0.233	-0.048	-0.035	-0.198	-0.201	-0.007	0.394	0.524	-0.745	-1.040	-0.470
14	1.006*)	0.355	0.488	1.562**	0.511	0.903*	2.455*	-0.120	0.951	7.363**	0.639	2.062*

No. of Expt.	combination of skewness and kurtosis						the W test					
10	1.044	0.995	0.987	0.764	1.049	1.209	0.968	0.969	0.970	0.972	0.969	0.969
11	0.006	0.415	0.378	0.936	0.249	0.646	0.971	0.971	0.972	0.956	0.972	0.968
12	1.484	1.326	1.055	5.133*	1.527	1.133	0.975	0.971	0.977	0.937	0.972	0.975
13	0.937	0.615	0.418	0.944	2.099	0.635	0.968	0.968	0.983	0.952	0.984	0.963
14	16.791**	0.843	3.080	107.728**	2.386	12.490**	0.942	0.982	0.974	0.823*	0.977	0.955

*) *,** = significance level at p=0.05 and p=0.01 respectively and will be used later with the same meaning.

TABLE 4.1.1.2 The coefficient of variation and the (%) of SS residuals for six standardizations of intercropping treatments.

	Coefficient of variation						The (%) of SS Residuals					
10	12.70	12.70	12.70	13.10	12.80	12.90	64.23	67.54	67.66	43.44	43.47	40.84
11	10.30	10.70	10.70	10.00	10.50	10.50	33.34	71.10	71.67	28.01	61.87	56.40
12	14.10	13.70	14.20	16.90	14.10	14.30	39.29	36.45	38.97	67.21	56.52	54.06
13	7.20	6.80	6.60	6.80	8.10	8.10	25.44	3.95	5.18	18.90	5.23	4.43
14	14.90	12.00	11.80	47.10	12.50	12.90	48.41	17.02	20.07	67.90	18.79	23.22

TABLE 4.1.1.3 Non-normality tests on the residuals of LER values for six standardizations of intercropping treatments based on coefficient of skewness and kurtosis.

No. of Expt.	Coefficient of skewness (g_1)						Coefficient of kurtosis (g_2)					
	L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}	L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}
1	no valid		0.162	no valid		0.465	no valid		0.113	no valid		1.855
5	solution		0.352	solution		0.046	solution		0.640	solution		0.312
6	0.475	0.211	0.232	-0.426	0.194	0.052	0.283	-0.060	-0.007	-0.651	-0.275	-0.418
7	-0.850	-0.966	-0.957	-0.562	-0.922	-0.974	-0.055	0.298	0.385	-0.574	0.135	-0.977
8	0.337	0.244	0.228	0.249	0.284	0.280	-1.195	-1.169	-1.193	-0.666	-0.823	-0.804
9	0.379	0.441	0.428	0.125	0.476	0.313	0.252	-0.087	0.012	0.124	-0.520	-0.446
10	-0.188	-0.186	-0.184	0.089	-0.163	-0.166	-0.864	-0.841	-0.845	-0.783	-0.886	-0.873
11	0.060	0.157	-0.129	0.466	-0.118	-0.119	0.206	0.506	0.505	-0.039	0.395	0.700
12	0.243	0.215	0.146	0.075	0.246	0.178	0.806	0.778	0.735	1.734*	0.818	0.739
13	0.380	0.233	-0.048	-0.035	0.198	-0.201	-0.007	0.394	0.524	-0.745	-1.040	-0.470
14	1.006*	0.355	0.488	1.562**	0.511	0.903*	2.455*	-0.120	0.951	7.363**	0.639	2.062*
15	0.021	0.187	0.204	-0.324	0.167	0.155	-0.706	-0.671	0.699	-0.707	-0.704	-0.838
17	-0.024	0.054	0.005	0.406	-0.327	-0.312	-0.891	-0.659	-0.634	-0.957	-0.702	-0.584
18	0.103	0.347	0.350	-0.511	-0.980	0.297	-0.355	-0.329	-0.329	0.244	1.943	-0.501
19	-0.034	-0.010	-0.045	-0.311	-0.033	-0.030	-1.484	-1.417	-1.445	-0.960	0.052	-1.420
20	-0.489	-0.449	-0.530	-0.425	-0.597	-0.402	-0.493	-0.558	-0.493	-0.396	-0.155	-0.455
22	0.000	0.000	0.000	0.000	0.000	0.000	-0.750	0.742	-0.588	-0.253	-0.644	-0.457
23	0.000	0.000	0.000	0.000	0.000	0.000	-1.261	-1.244	-1.269	-1.135	-1.105	-1.163
24	0.153	0.042	0.002	-0.228	0.024	-0.048	-0.543	-0.685	-0.539	-0.491	-0.657	-0.457

TABLE 4.1.1.4 Non-normality tests on the residuals of LER values for six standardizations of intercropping treatments based on joint use of skewness and kurtosis coefficients and the W test.

No. of Expt.	Combination of skewness & kurtosis						W test					
	L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}	L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}
1	no valid		0.133	no valid		5.050*	no valid		0.965	no valid		0.920
5	solution		1.042	solution		0.125	solution		0.960	solution		0.973
6	0.858	0.158	0.187	1.205	0.201	0.171	0.964	0.991	0.991	0.965	0.988	0.987
7	2.270	3.004	3.001	1.268	2.684	3.783	0.890*	0.897	0.903	0.845*	0.886*	0.920
8	1.963	1.684	1.713	0.717	1.036	0.998	0.919	0.944	0.944	0.967	0.961	0.951
9	0.639	0.783	0.728	0.078	1.188	0.601	0.964	0.975	0.978	0.972	0.955	0.972
10	1.044	0.995	0.987	0.764	1.049	1.029	0.968	0.969	0.970	0.972	0.969	0.969
11	0.006	0.415	0.378	0.936	0.249	0.646	0.971	0.971	0.972	0.956	0.972	0.968
12	1.484	1.326	1.055	5.133*	1.527	1.133	0.975	0.971	0.977	0.937	0.972	0.975
13	0.937	0.615	0.418	0.944	2.099	0.635	0.968	0.968	0.983	0.952	0.984	0.963
14	16.791**	0.843	3.080	107.728**	2.386	12.490**	0.942	0.982	0.974	0.823**	0.977	0.955
15	0.594	0.690	0.767	1.066	0.854	0.943	0.989	0.976	0.972	0.957	0.967	0.963
17	0.807	0.452	0.408	1.559	0.908	0.717	0.950	0.934	0.933	0.944	0.949	0.955
18	0.281	0.965	0.978	1.793	12.638**	0.999	0.987	0.967	0.967	0.969	0.936	0.968
19	1.454	1.323	1.380	0.845	1.256	1.330	0.920	0.932	0.927	0.953	0.953	0.932
20	1.057	0.989	1.201	0.773	1.263	0.755	0.961	0.963	0.959	0.970	0.950	0.968
22	0.688	0.654	0.411	0.076	0.492	0.248	0.980	0.981	0.987	0.962	0.987	0.987
23	1.887	1.838	1.910	1.530	1.449	1.608	0.938	0.946	0.945	0.949	0.963	0.968
24	0.504	0.626	0.382	0.576	0.570	0.286	0.979	0.971	0.976	0.984	0.972	0.974

TABLE 4.1.1.5 The coefficient of variation and the percentage of sum squares of residuals of LER values for six standardizations of intercropping treatments.

No. of Expt.	The coefficient of variation (%)						(%) of SS of residuals					
	L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}	L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}
1	no valid		10.60	no valid		7.20	no valid		40.96	no valid		14.20
5	solution		9.20	solution		8.80	solution		30.61	solution		23.07
6	10.60	7.90	7.90	9.80	7.90	8.30	45.91	31.80	35.25	58.50	38.31	49.78
7	5.70	7.10	6.30	8.60	8.20	7.10	92.84	6.76	8.30	70.95	7.03	9.54
8	7.50	7.40	8.20	7.90	7.70	8.00	35.66	12.66	16.30	15.02	8.02	10.15
9	14.10	12.80	12.90	15.10	13.10	13.20	44.51	40.46	39.14	17.41	14.60	26.92
10	12.70	12.70	12.70	13.10	12.80	12.90	64.23	67.54	67.66	43.44	43.47	40.84
11	10.30	10.70	10.70	10.00	10.50	10.50	33.34	71.10	71.67	28.01	61.87	56.40
12	14.10	13.70	14.20	16.90	14.10	14.30	39.29	36.45	38.97	67.21	56.52	54.06
13	7.20	6.80	6.60	6.80	8.10	6.40	25.44	3.95	5.18	18.90	5.23	4.43
14	14.90	12.00	11.80	47.10	12.50	12.90	48.41	17.02	20.07	67.90	18.79	23.22
15	15.30	16.50	18.10	12.80	16.60	18.50	57.44	37.67	45.94	74.08	38.96	53.20
17	3.70	3.90	3.80	3.90	3.80	3.70	2.64	1.63	1.50	3.12	1.59	1.47
18	8.70	8.40	8.40	9.40	10.30	8.80	29.15	16.25	16.44	19.89	23.93	16.87
19	5.10	4.90	4.70	5.60	4.80	4.70	7.26	6.73	7.06	8.10	5.84	6.17
20	14.30	14.60	16.80	13.00	14.30	16.90	60.05	23.55	38.15	61.42	21.69	31.62
22	13.70	12.30	13.20	13.30	12.40	13.80	6.62	5.18	5.13	6.83	5.56	5.79
23	10.50	10.70	10.80	10.90	11.40	11.50	27.54	25.45	27.64	9.79	10.97	10.20
24	8.90	8.50	8.50	12.20	8.50	8.50	17.04	19.49	20.46	25.30	19.31	18.59

TABLE 4.1.1.6 Non-normality tests in the residuals of LER values for three standardizations including sole crop treatments.

No. of Expt.	Skewness Coefficient			Kurtosis coefficient			Joint of skewness & kurtosis			W test		
	L_{11}	L_{21}	L_{31}	L_{11}	L_{21}	L_{31}	L_{11}	L_{21}	L_{31}	L_{11}	L_{21}	L_{31}
6	0.422	0.489	0.486	0.451	1.050	1.033	1.271	2.900	2.834	0.972	0.955	0.949
7	2.502*	-0.621	-0.558	13.965**	1.375	1.079	481.965**	7.425*	5.198	0.757**	0.974	0.973
8	1.307	0.309	0.292	5.427**	-0.625	-0.429	70.149**	1.475	0.996	0.898**	0.967	0.974
9	0.262	0.258	0.315	0.557	0.157	0.585	1.117	0.546	1.408	0.976	0.987	0.987
16	-0.653	-0.533	-0.488	-0.625	-0.786	-0.695	3.433	2.887	2.367	0.912**	0.891**	0.901*
17	0.349	0.368	0.470	-0.098	-0.206	0.058	0.974	1.145	1.735	0.774**	0.980	0.977
20	-0.230	-0.166	-0.225	0.147	0.295	0.464	0.381	0.326	0.694	0.978	0.980	0.969
21	0.263	0.241	0.215	-0.861	-0.736	-0.830	1.191	0.904	1.024	0.957	0.960	0.953
22	0.000	0.000	0.000	0.325	0.128	0.581	0.233	0.036	0.742	0.979	0.960	0.967
23	0.000	0.000	0.000	-0.495	-0.506	-0.387	0.538	0.563	0.329	0.880	0.968	0.976
24	0.096	0.092	0.060	-0.676	-0.819	-0.645	1.207	1.722	1.052	0.967	0.956	0.968

TABLE 4.1.1.7 The coefficient of variation and the percentage of SS residuals for three standardizations including the sole crop treatments.

No. of Expt.	Coefficient of variation (%)			The (%) of SS residuals		
	L_{11}	L_{21}	L_{31}	L_{11}	L_{21}	L_{31}
6	11.50	9.40	9.30	18.13	20.65	18.27
7	15.70	6.80	6.20	36.60	4.17	3.52
8	11.70	6.60	7.30	18.27	4.77	5.01
9	16.40	15.00	15.10	8.97	7.32	10.87
16	9.20	10.10	10.30	13.11	7.19	6.36
17	5.50	5.50	5.60	3.18	2.29	2.23
20	13.10	13.70	16.50	19.78	9.98	11.19
21	6.50	6.10	6.30	5.95	4.25	3.61
22	9.50	8.80	9.60	5.77	4.23	4.69
23	9.30	9.60	10.00	9.30	8.33	5.67
24	9.90	9.20	9.20	12.96	11.09	8.06

TABLE 4.1.1.8 Homogeneity of variance tests on residuals of LER values for six standardizations of intercropping treatments for one-way classification.

No. of Expt.	Treatments	Bartlett's test (χ^2)						Modification of Bartlett's test (χ^2)						Layard test (χ^2)					
		L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}	L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}	L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}
1	Population of peanut	no valid		2.36	no valid		1.15	no valid		2.24	no valid		1.17	no valid		2.84	no valid		1.79
5	Date of cassava planting	solution		2.16	solution		6.61	solution		3.80	solution		7.08	solution		4.36	solution		7.31
7	N fertilizers of of maize & peanut	8.53*	11.87**	10.93*	7.57	15.56**	11.80**	6.02	6.80	6.62	6.86	8.46	4.25	9.51*	12.24**	12.54**	12.07**	16.68**	6.06
8	Genotypes of mung bean	1.98	2.22	1.45	1.47	1.65	1.64	4.68	4.95	3.68	3.03	3.61	2.72	1.98	5.03	3.32	2.41	3.24	3.27
9	Genotypes of soybean	3.58	4.93	4.86	2.33	2.53	3.52	3.58	5.21	4.71	3.54	4.58	5.38	3.58	6.41	5.41	3.06	4.50	5.74
17	Date of planting of corn & peanut	4.25	4.81	4.59	0.59	5.19	6.66	3.95	4.34	4.02	1.23	4.62	4.55	5.06	5.70	5.15	1.05	6.64	6.36

TABLE 4.1.1.9 Homogeneity of variance tests on residuals of LER values for six standardizations of intercropping treatments for two-way classifications (Bartlett's test).

No. of Expt.	The 1st factors	χ^2 L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}	The 2nd factors	χ^2 L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}
6	Population of maize	1.18	0.40	0.55	0.47	1.56	1.07	N fertilizer in maize	3.36	2.08	2.68	0.29	2.09	1.78
10	The direction of rows planting	0.04	0.08	0.08	0.25	0.14	0.16	Genotypes of soybean	0.98	1.46	1.45	2.48	2.86	3.55
11	The direction of rows planting	0.04	0.08	0.01	0.09	0.56	0.12	Genotypes of soybean	1.69	1.89	1.86	3.90	2.83	1.32
12	Genotypes of maize	1.72	0.70	0.69	0.16	0.20	0.13	Genotypes of soybean	3.62	2.33	2.40	5.63	3.05	2.38
13	Genotypes of maize	1.04	0.50	0.45	0.23	0.62	0.58	Genotypes of mungbean	3.51	6.64	4.07	2.08	7.43	6.21
14	Genotypes of maize	1.99	1.72	2.86	11.08*	1.37	2.33	Genotypes of mungbean	5.04	2.17	1.34	48.70**	1.12	1.63
15	Planting distance of maize	0.51	2.28	1.55	1.31	0.73	1.16	Planting distance of soybean	2.23	0.88	1.67	4.51	1.38	1.87
18	Date of maize planting	0.36	0.31	0.31	1.07	0.46	1.25	Population of maize	3.34	1.70	1.63	2.54	5.28	1.40
19	Population of maize	1.41	0.002	0.24	1.18	0.01	0.21	Genotypes of maize	0.23	2.29	2.24	0.02	1.28	1.21
20	Genotypes of maize	1.85	2.78	2.58	3.96	2.22	2.37	Population of maize	0.28	0.92	0.89	0.32	0.88	0.61
22	Genotypes of maize	6.56	6.05	6.58	3.31	5.71	6.33	Leaf cutting of maize	0.003	0.002	0.003	0.17	0.04	0.01
23	Genotypes of maize	3.01	2.93	2.35	1.35	1.60	2.17	Leaf cutting of maize	0.58	0.17	0.30	0.46	0.60	0.59
24	Genotypes of maize	0.003	1.04	0.77	0.01	0.97	0.71	Leaf cutting of maize	0.95	0.43	0.63	0.41	0.42	0.68

TABLE 4.1.1.10 Homogeneity of variance tests on residuals of LER values for six standardizations of intercropping treatments for two-way classifications based on Box's modification of Bartlett's test.

No. of Expt.	The 1st factor	χ^2 L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}	The 2nd factor	χ^2 L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}
6	Population of maize	1.51	0.59	0.79	0.60	1.51	1.11	N fertilizer on maize	2.20	3.59	4.08	0.35	2.29	1.92
10	The direction of rows planting	0.05	0.09	0.09	0.24	0.14	0.15	Genotypes of soybean	1.82	2.25	2.24	4.18	4.25	5.01
11	The direction of rows planting	0.03	0.06	0.05	0.08	0.42	0.10	Genotypes of soybean	2.28	1.53	1.57	4.83	2.10	1.25
12	Genotypes of maize	1.72	0.64	0.55	0.10	0.17	0.11	Genotypes of soybean	3.62	2.43	2.22	2.91	2.39	1.95
13	Genotypes of maize	1.00	0.52	0.47	0.36	0.67	0.68	Genotypes of mungbean	5.92	10.37	5.74	3.90	1.63	1.70
14	Genotypes of maize	0.67	1.43	1.89	1.04	0.85	1.33	Genotypes of mungbean	4.02	3.91	2.47	13.04*	7.62	10.93*
15	Planting distance of maize	0.47	2.10	1.34	1.36	0.74	1.38	Planting distance of soybean	2.35	0.75	1.24	6.00	1.56	2.02
18	Date of maize planting	0.82	0.58	0.57	2.58	1.06	2.03	Population of maize	3.14	1.81	1.73	2.13	1.33	2.55
19	Population of maize	1.51	0.04	0.34	1.09	0.02	0.28	Genotypes of maize	0.61	5.06*	4.65*	0.04	2.99	2.79
20	Genotypes of maize	3.33	2.23	2.49	3.17	1.96	2.38	Population of maize	0.52	0.89	0.70	0.42	0.91	2.12
22	Genotypes of maize	4.85	4.90	5.04	5.16	6.72	5.42	Leaf cutting of maize	0.01	0.004	0.01	0.36	0.09	0.03
23	Genotypes of maize	5.60	5.71	4.68	2.45	2.42	3.02	Leaf cutting of maize	0.66	0.18	0.32	0.62	0.50	0.50
24	Genotypes of maize	0.01	1.69	1.32	0.01	1.36	1.10	Leaf cutting of maize	1.30	0.57	0.78	0.81	0.62	0.85

TABLE 4.1.1.11 Homogeneity of variance tests on residuals of LER values for six standardizations of intercropping treatments for two-way classification based on Layard's test.

No. of Expt.	The 1st factor	χ^2 L_{11}	L_{21}	L_{31}	L_{12}	L_{22}	L_{32}	The 2nd factor	χ^2 L_{11}	L_{21}	L_{31}	L_{21}	L_{22}	L_{32}
6	Population of maize	1.60	0.60	0.81	0.62	1.67	1.21	N fertilizer on maize	2.97	3.28	3.90	0.35	2.79	1.93
10	The direction of rows planting	0.05	0.10	0.10	0.25	0.13	0.16	Genotypes of soybean	1.66	2.07	2.06	4.55	4.71	5.79
11	The direction of rows planting	0.03	0.06	0.05	0.08	0.45	0.10	Genotypes of soybean	2.65	1.57	1.60	5.69	2.15	1.28
12	Genotypes of maize	1.72	0.66	0.57	0.10	0.18	0.11	Genotypes of soybean	2.65	2.46	2.22	3.06	2.71	2.15
13	Genotypes of maize	1.05	0.53	0.49	0.36	0.68	0.69	Genotypes of mungbean	7.83	4.46	7.86	3.58	1.80	1.76
14	Genotypes of maize	0.73	1.51	2.04	1.26	0.90	1.44	Genotypes of mungbean	15.22*	4.31	2.67	19.45*	7.11	14.10*
15	Planting distance of maize	0.50	2.29	1.45	1.45	0.78	1.45	Planting distance of soybean	2.85	0.82	1.52	6.70	1.95	2.64
18	Date of maize planting	0.76	0.56	0.56	2.58	1.04	2.13	Population of maize	3.14	1.99	1.90	2.49	1.48	2.66
19	Population of maize	1.73	0.004	0.35	1.27	0.02	1.61	Genotypes of maize	0.53	5.03*	4.65*	0.04	2.82	2.63
20	Genotypes of maize	2.97	2.59	2.55	3.37	2.16	2.54	Population of maize	0.51	0.97	0.77	0.43	0.98	0.57
22	Genotypes of maize	4.75	5.21	5.28	4.83	6.99	6.10	Leaf cutting of maize	0.01	0.004	0.01	0.35	0.08	0.03
23	Genotypes of maize	6.54	6.80	5.33	2.53	2.54	3.17	Leaf cutting of maize	0.69	0.19	0.34	0.63	0.54	0.54
24	Genotypes of maize	0.01	1.58	1.24	0.01	1.39	1.05	Leaf cutting of maize	1.43	0.59	0.84	0.77	0.62	0.87

TABLE 4.1.1.12 Homogeneity of variance test of residuals of L_{11}, L_{21} and L_{31} including sole crop treatments based on Bartlett's, Box's modification of Bartlett's and Layard's test.

Bartlett's test

No. of Expt.	The 1st factor	χ^2 L_{11}	L_{21}	L_{31}	The 2nd factor	χ^2 L_{11}	L_{21}	L_{31}	The 3rd factor	χ^2 L_{11}	L_{21}	L_{31}
8	Planting systems	14.33**	1.99	1.34	Mungbean genotypes	4.64	1.22	1.03	These were not the 3rd factor	—	—	—
9	" "	1.27	0.01	0.38	Soybean genotypes	1.00	0.75	0.62	" "	—	—	—
16	" "	7.31**	7.29**	5.84*	Weeding methods	1.30	0.34	0.45	" "	—	—	—
19	" "	21.98**	0.01	0.03	Maize densities	0.69	3.03	0.25	Maize genotypes	1.99	0.87	1.15
20	" "	11.59**	0.04	0.10	Maize genotypes	1.54	1.19	0.86	Maize densities	0.44	0.03	0.26
22	" "	23.14**	7.44**	11.35**	" "	13.21**	6.00*	4.17	Leaf cutting of corn	0.02	0.04	0.04
23	" "	11.67**	0.92	2.01	" "	0.95	1.52	1.15	" "	0.01	0.01	0.001
24	" "	7.37**	0.21	0.75	" "	7.29*	5.69	5.20	" "	8.56*	4.38	6.89*

Bartlett's modified test

No. of Expt.	The 1st factor	L_{11}	L_{21}	L_{31}	The 2nd factor	L_{11}	L_{21}	L_{31}	The 3rd factor	L_{11}	L_{21}	L_{31}
8	Planting systems	4.68*	2.97	2.06	Mungbean genotypes	2.73	0.89	0.96	These were not the 3rd factor	—	—	—
9	" "	1.54	0.01	0.67	Soybean genotypes	2.19	1.75	1.70	" "	—	—	—
16	" "	7.19**	8.45**	7.35**	Weeding methods	2.15	0.72	0.93	" "	—	—	—
19	" "	11.65**	0.01	0.07	Maize densities	1.34	3.87	3.44	Maize genotypes	5.03*	1.93	3.06
20	" "	9.54**	0.04	0.09	Maize genotypes	3.53	1.81	1.94	Maize densities	0.90	0.03	0.34
22	" "	21.56**	8.37*	11.94**	" "	14.68**	9.67**	6.53*	Leaf cutting of corn	0.001	0.03	0.04
23	" "	7.30**	0.66	1.44	" "	1.85	3.09	3.43	" "	0.01	0.01	0.001
24	" "	7.65**	0.33	1.11	" "	9.38**	8.42*	9.15*	" "	9.69**	6.14*	9.40**

Layard's test

No. of Expt.	The 1st factor	L_{11}	L_{21}	L_{31}	The 2nd factor	L_{11}	L_{21}	L_{31}	The 3rd factor	L_{11}	L_{21}	L_{31}
8	Planting systems	5.59*	3.03	2.08	Mungbean genotypes	2.64	1.02	1.03	These were not the 3rd factor			
9	" "	1.58	0.01	0.66	Soybean genotypes	1.97	1.53	1.40	" "			
16	" "	6.92*	10.26**	8.72**	Maize densities	2.10	0.67	0.86	" "			
19	" "	17.64**	0.01	0.07	Maize genotypes	1.32	4.14	3.54	Maize genotypes	4.82	1.86	2.87
20	" "	11.14**	0.004	0.10	" "	3.44	1.76	1.90	Maize densities	0.88	0.03	0.34
22	" "	26.12**	8.98**	13.23**	" "	16.05**	9.21**	6.05*	Leaf cutting of corn	0.001	0.04	0.03
23	" "	8.25**	0.68	1.52	" "	1.91	3.01	3.09	" "	0.01	0.01	0.001
24	" "	8.17**	0.33	1.12	" "	9.29**	8.23*	9.19*	" "	11.92**	6.41*	10.47**

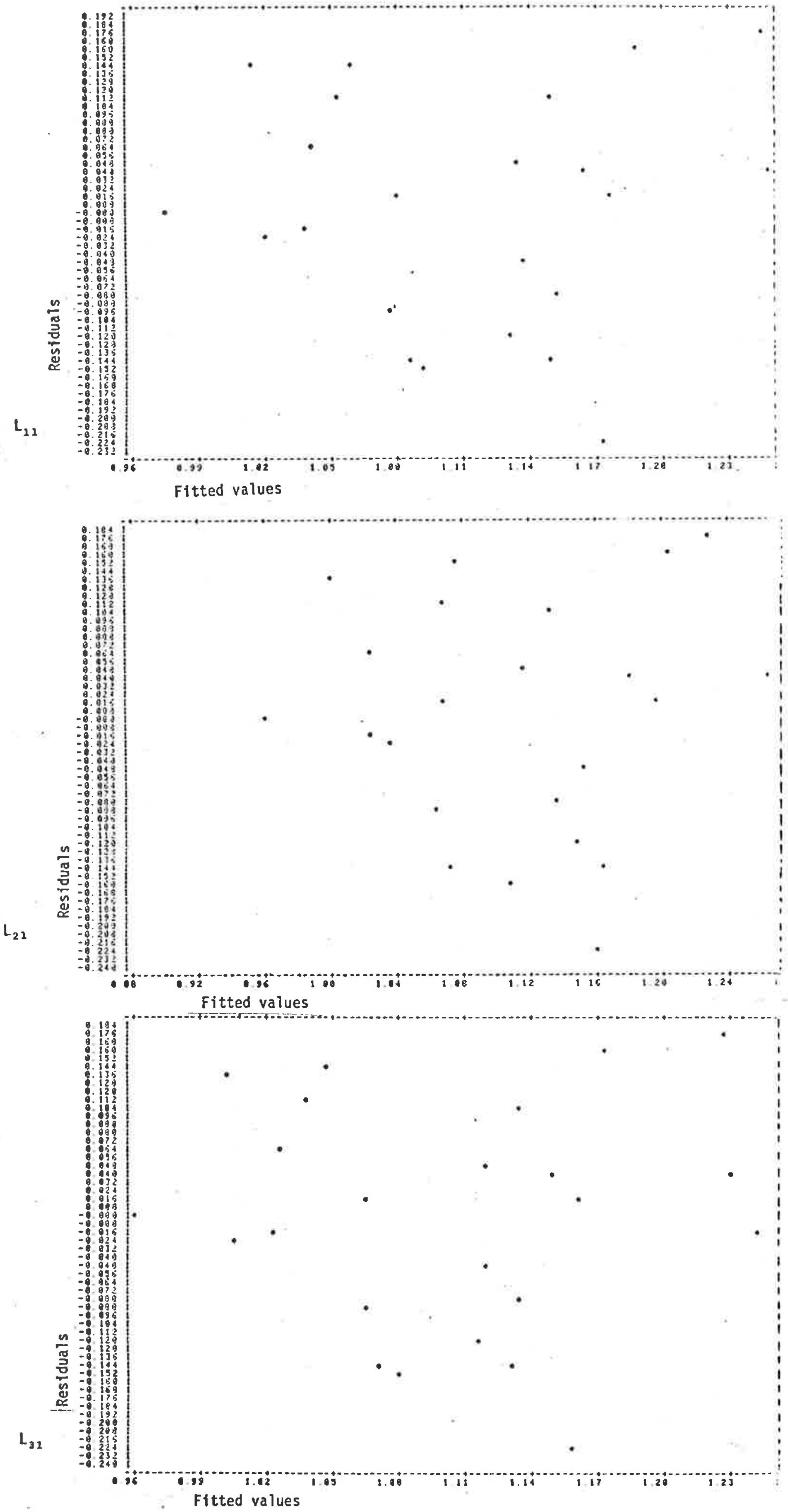


Fig. 4.1.1.1 Plot of residuals against fitted values of experiment 10 of average block standardization. (L_{11}, L_{21}, L_{31}) of intercropping treatments.

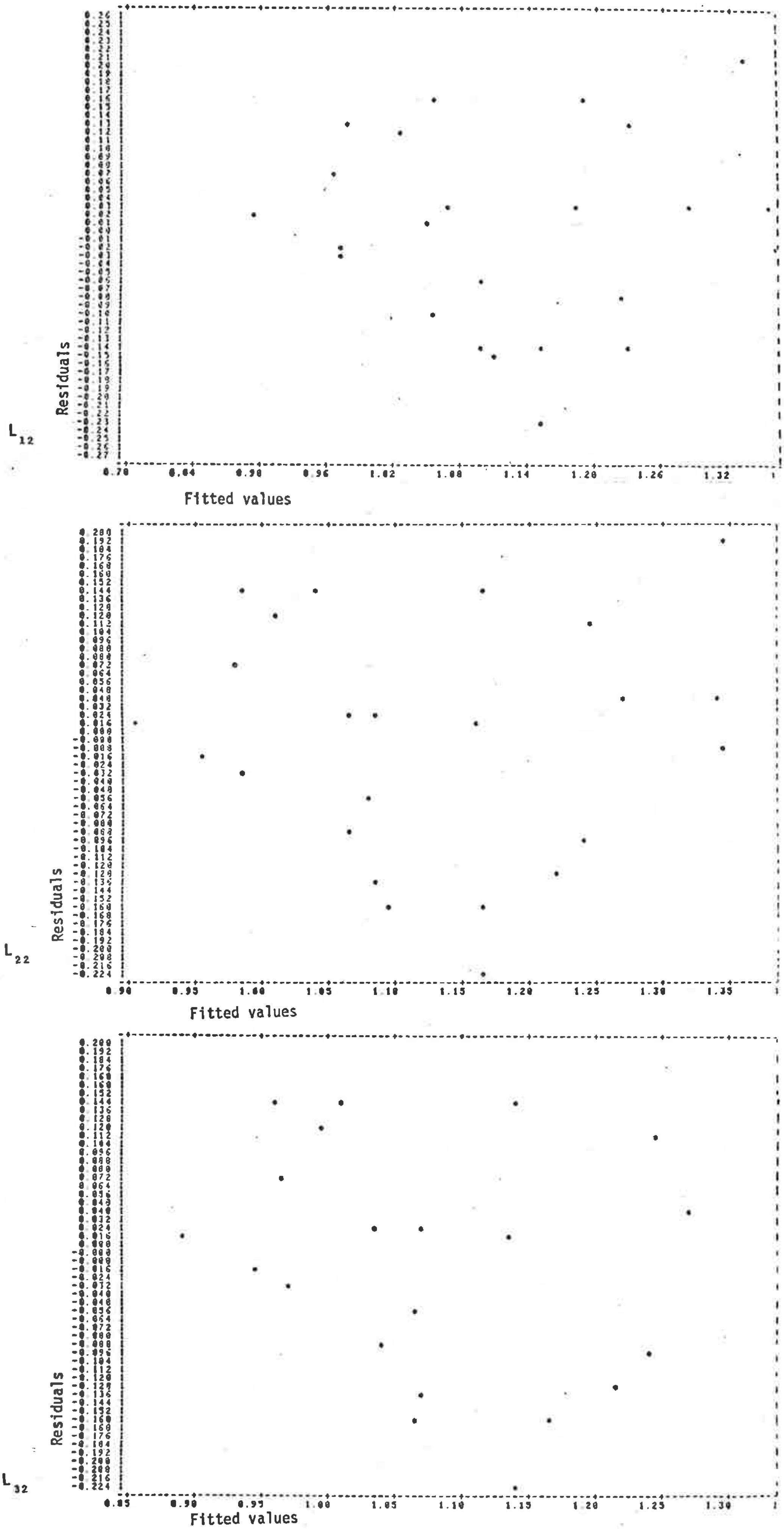
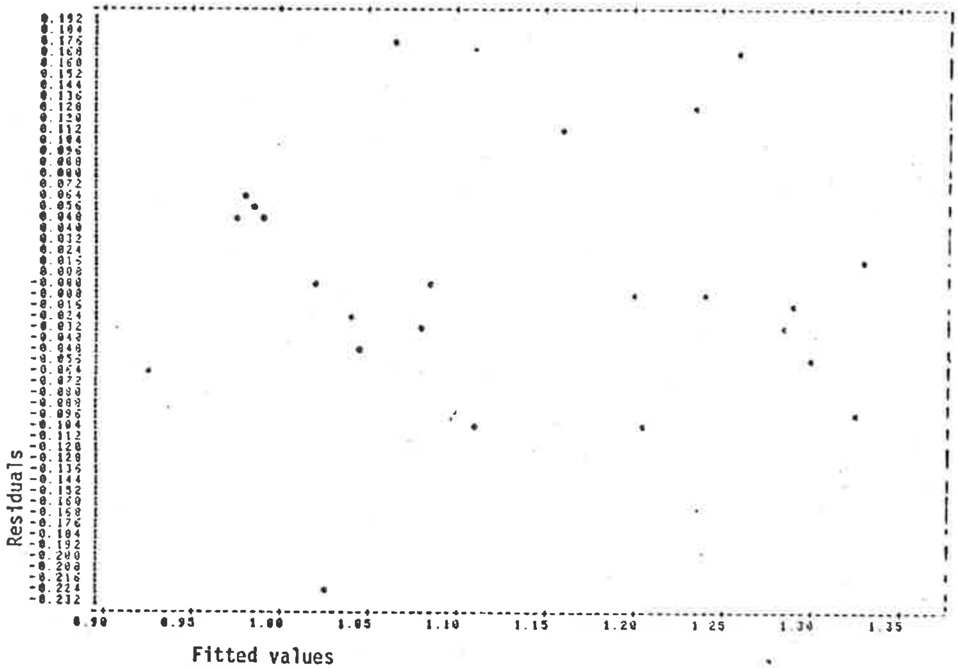
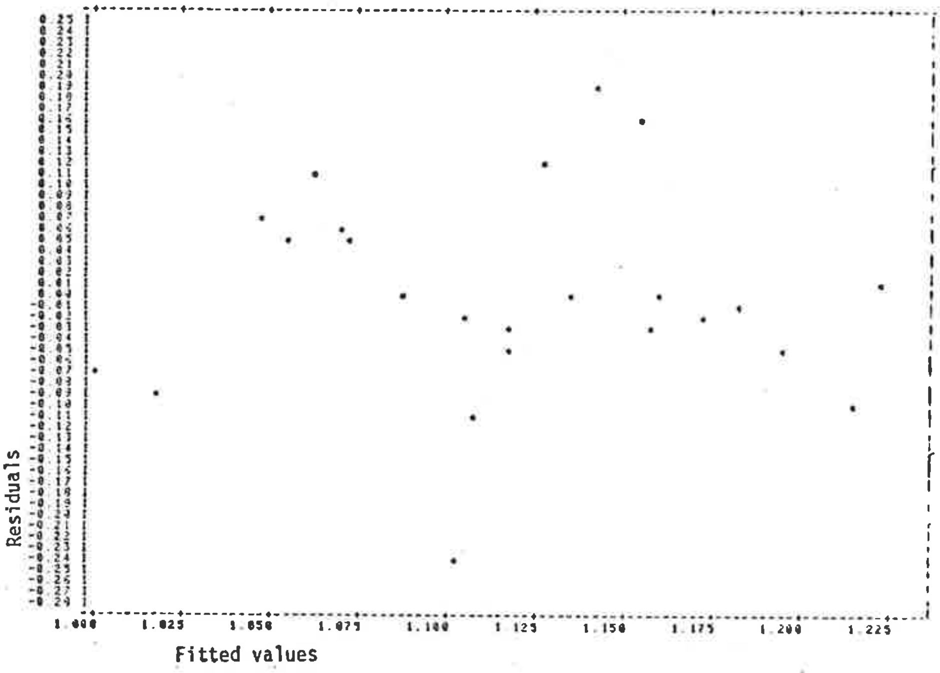


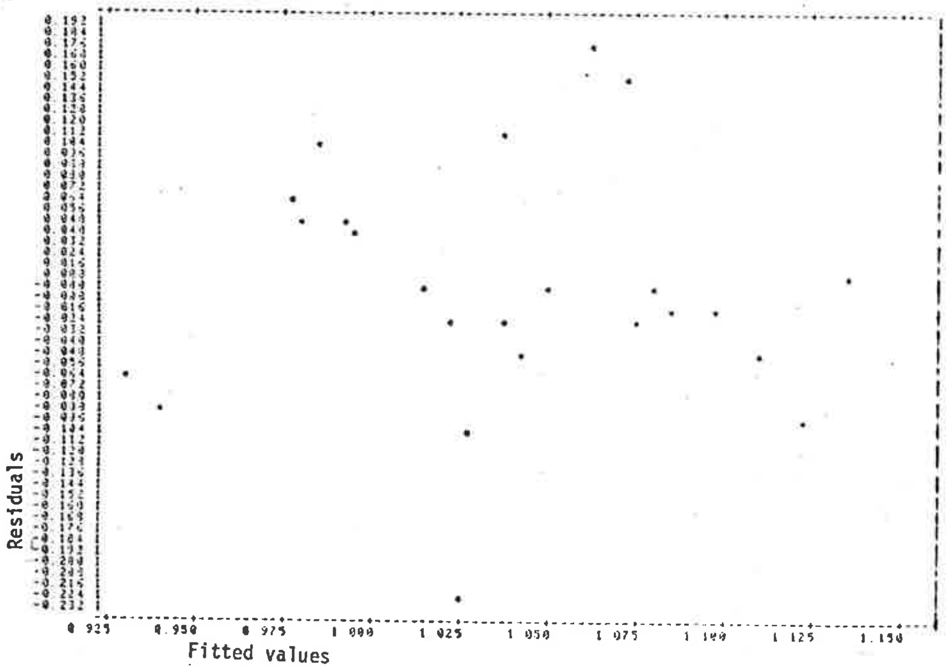
Fig. 4.1.1.2 Plot of residuals against fitted values of experiment 10 of each block standardizations (L_{12}, L_{22}, L_{32}) of intercropping treatments.



L_{11}



L_{21}



L_{31}

Fig. 4.1.1.3 Plot of residuals against fitted values of experiment 11 of average block standardization (L_{11}, L_{21}, L_{31}) of intercropping treatments.

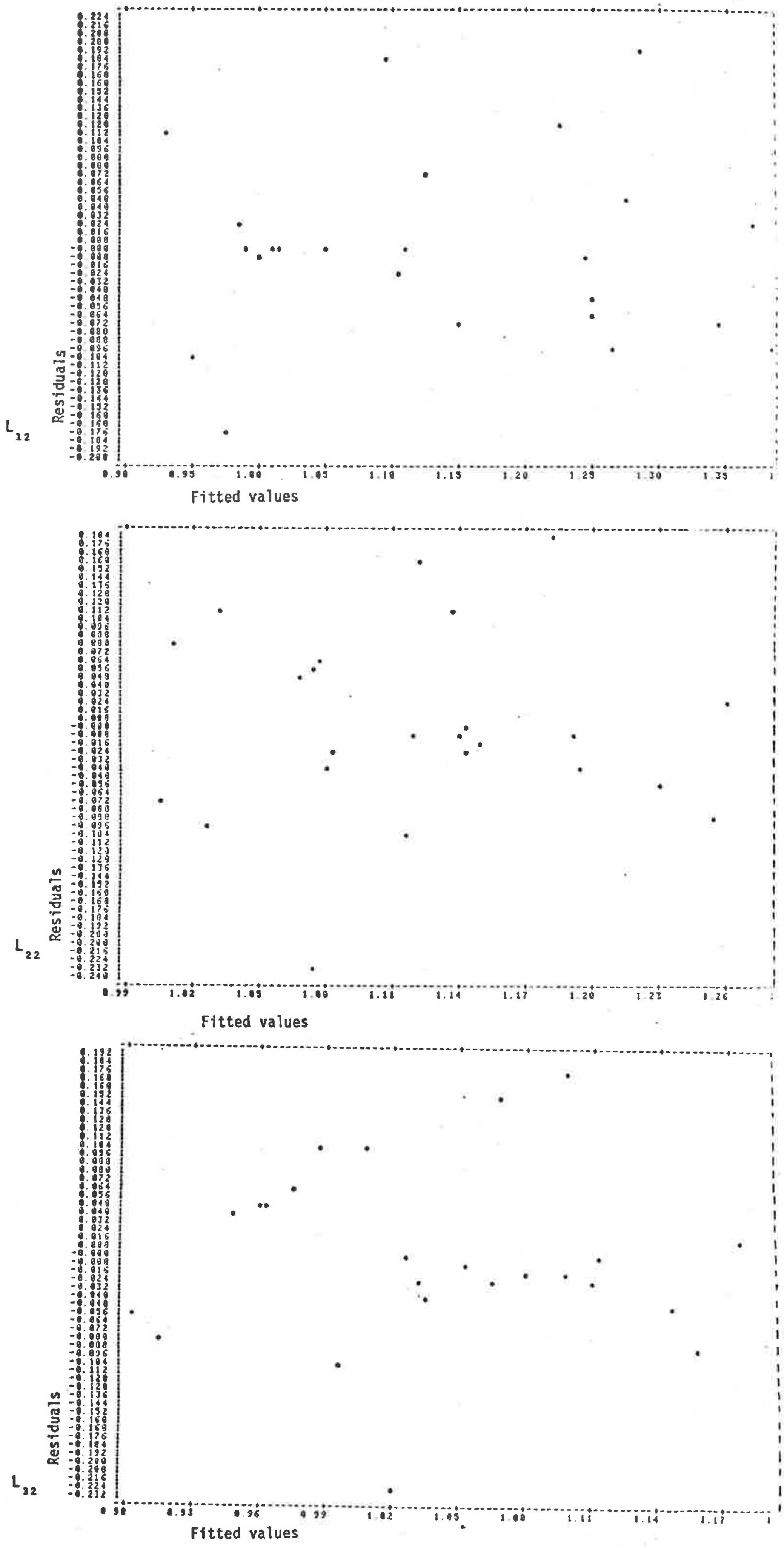


Fig. 4.1.1.4 Plot of residuals against fitted values of experiment 11 of each block standardization (L_{12}, L_{22}, L_{32}) of intercropping treatments.

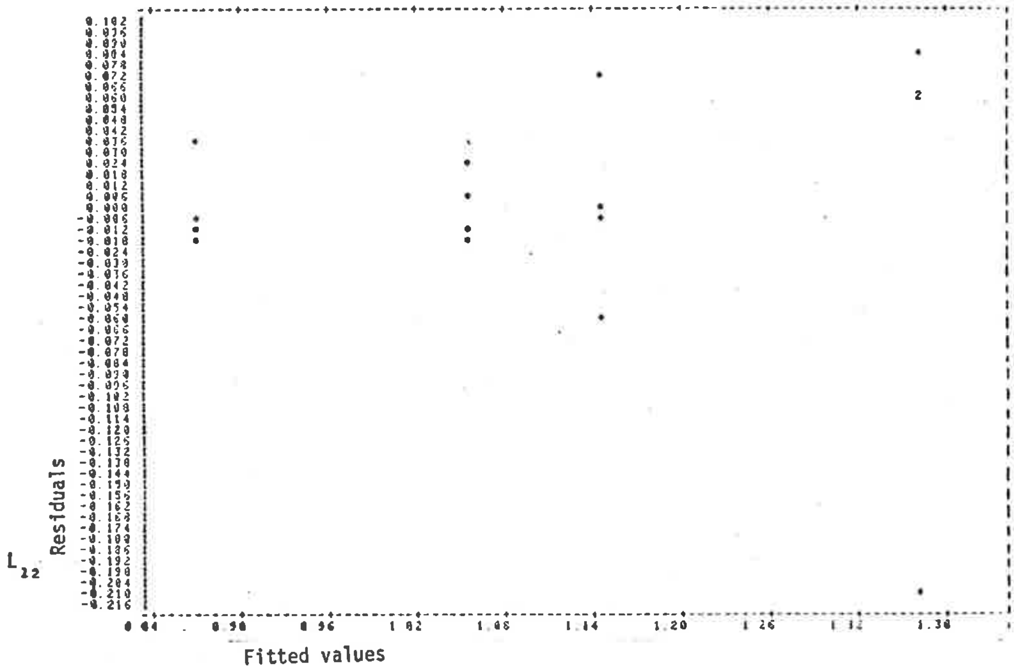


Fig. 4.1.1.5 Plot of residuals against fitted values of L_{12} of experiment 7 of intercropping treatments.

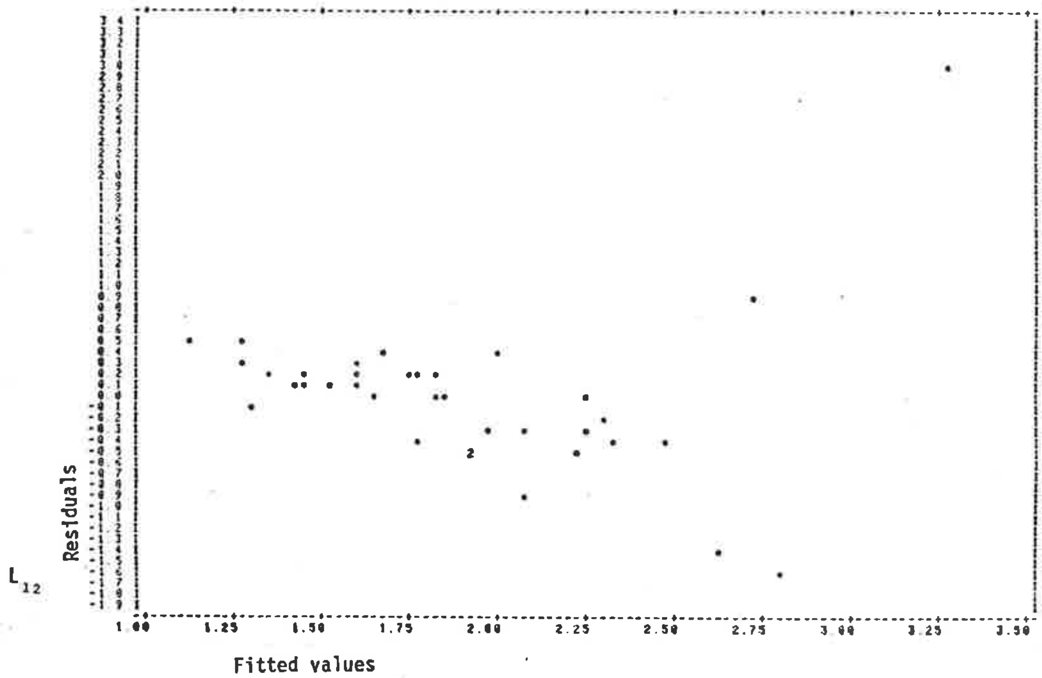


Fig. 4.1.1.6 Plot of residuals against fitted value of L_{12} of experiment 14 of intercropping treatments.

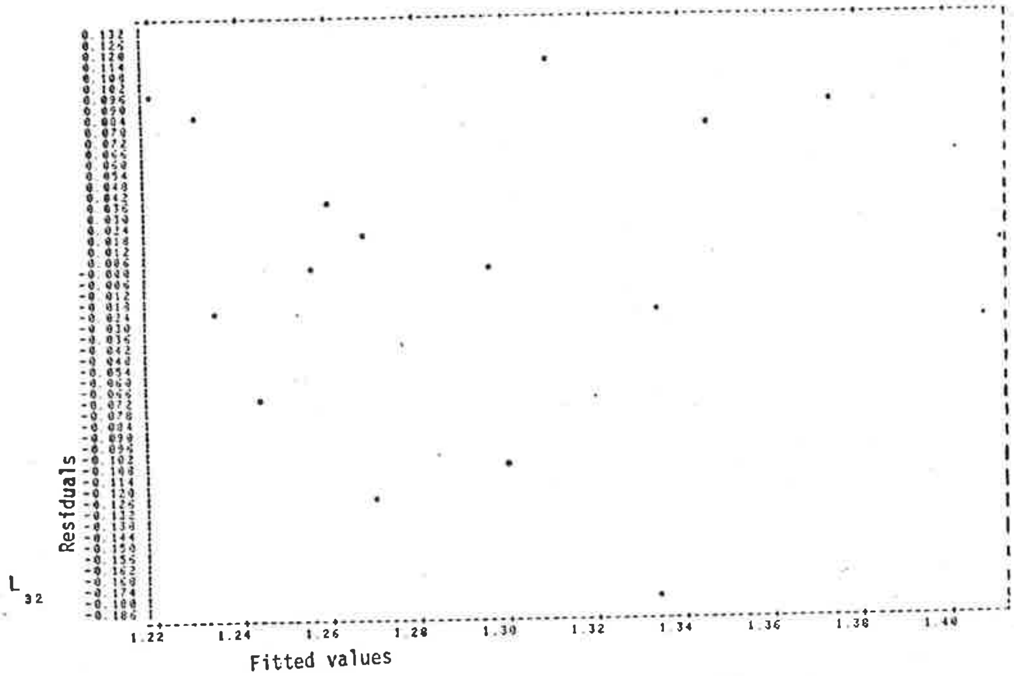
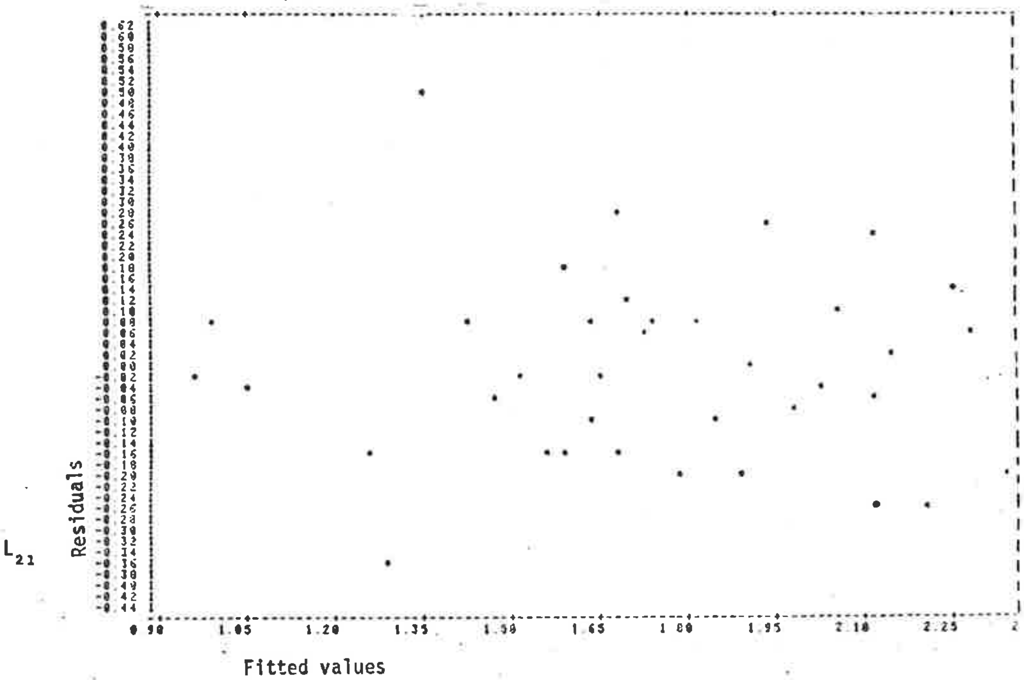


Fig. 4.1.1.7 Plot of residuals against fitted values of L_{32} of experiment 7 of intercropping treatments.



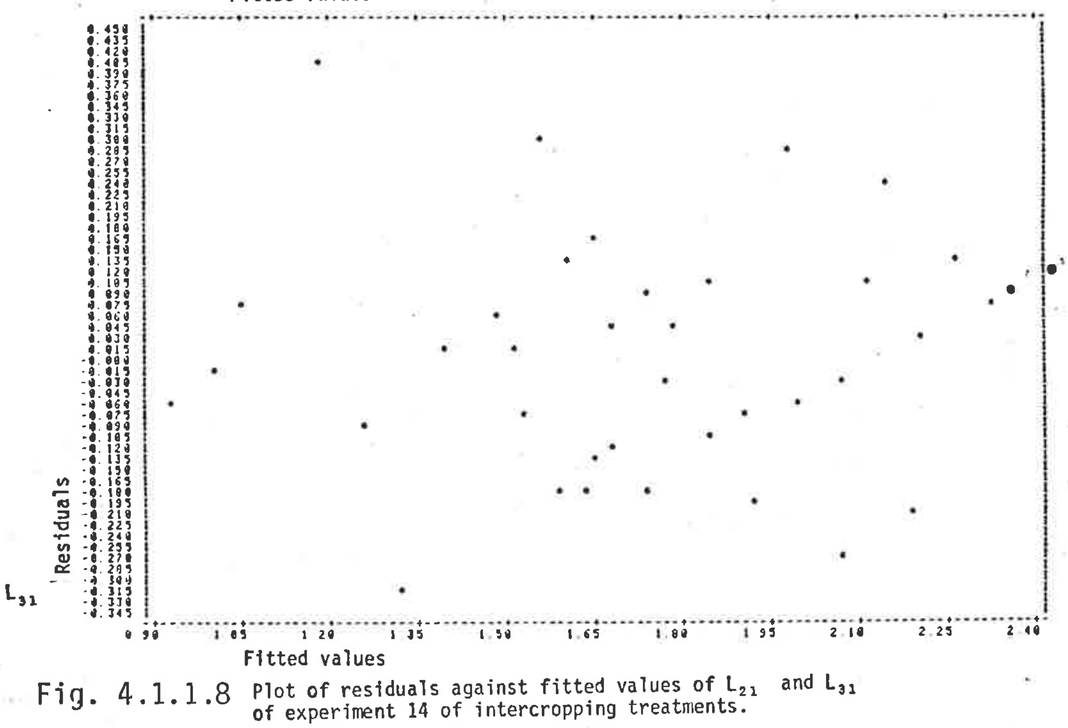


Fig. 4.1.1.8 Plot of residuals against fitted values of L_{21} and L_{31} of experiment 14 of intercropping treatments.

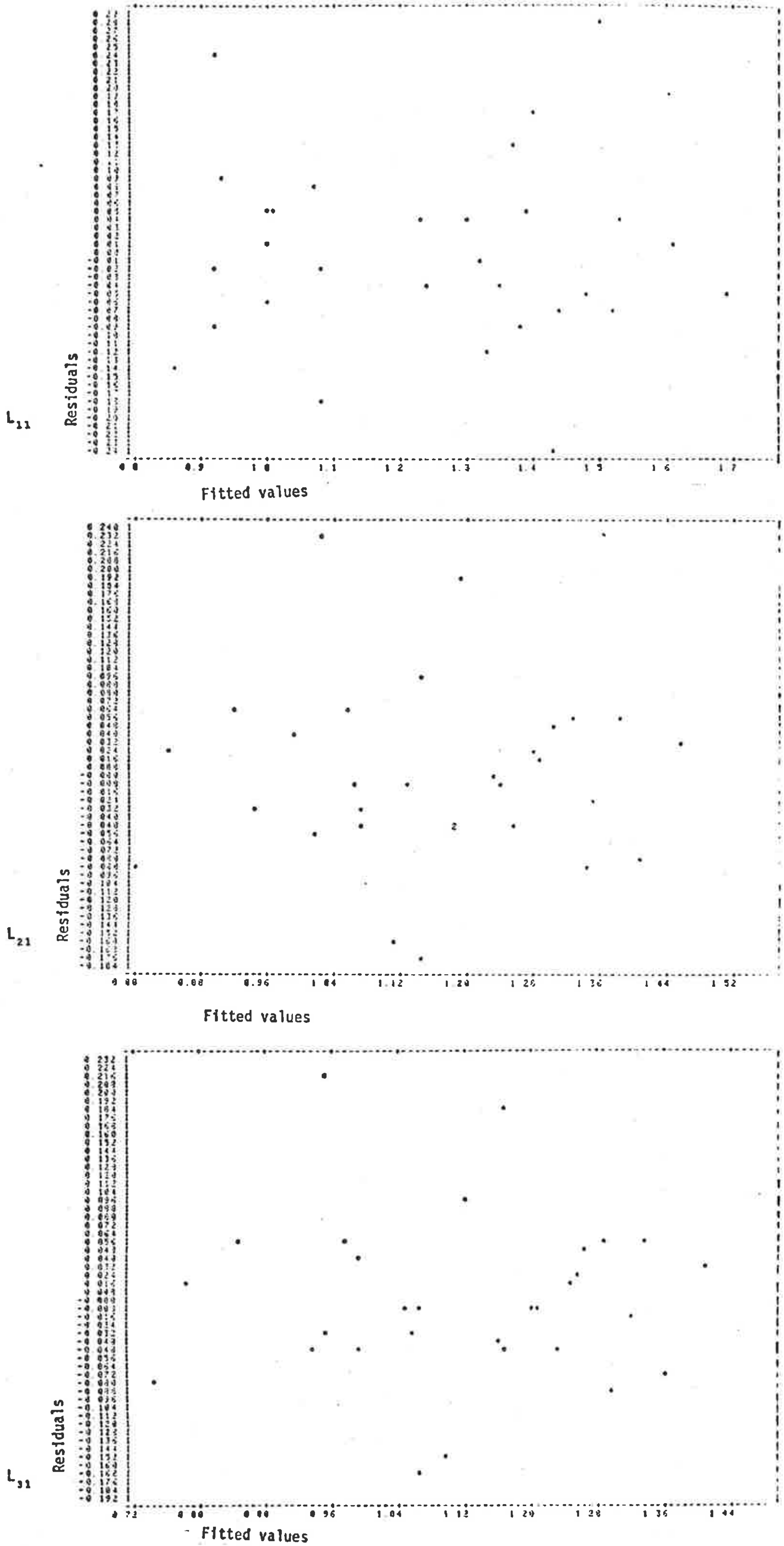


Fig. 4.1.1.9 Plot of residuals against fitted values of L_{11}, L_{21}, L_{31} of experiment 6 including sole crop treatments.

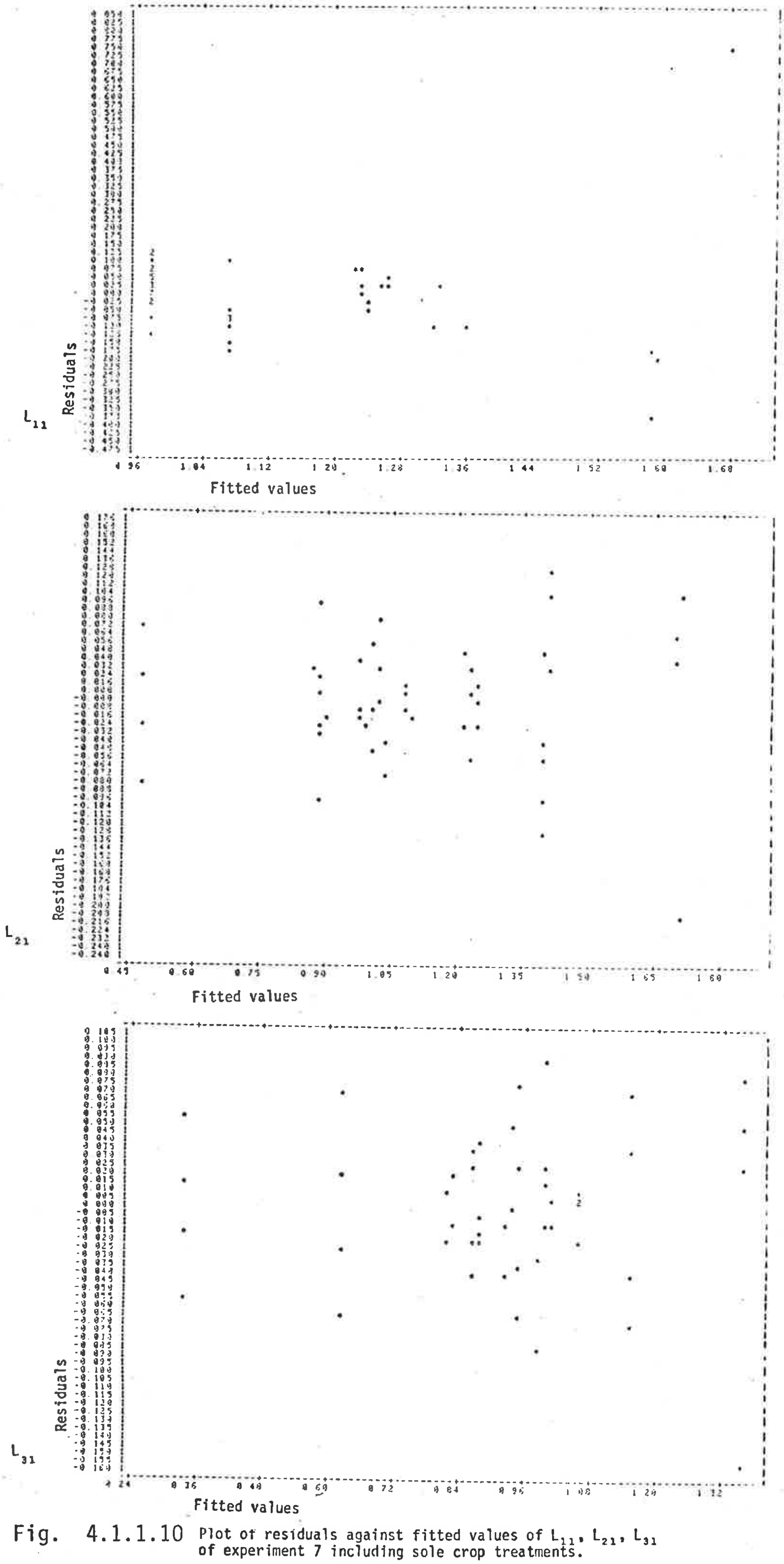


Fig. 4.1.1.10 Plot of residuals against fitted values of L_{11}, L_{21}, L_{31} of experiment 7 including sole crop treatments.

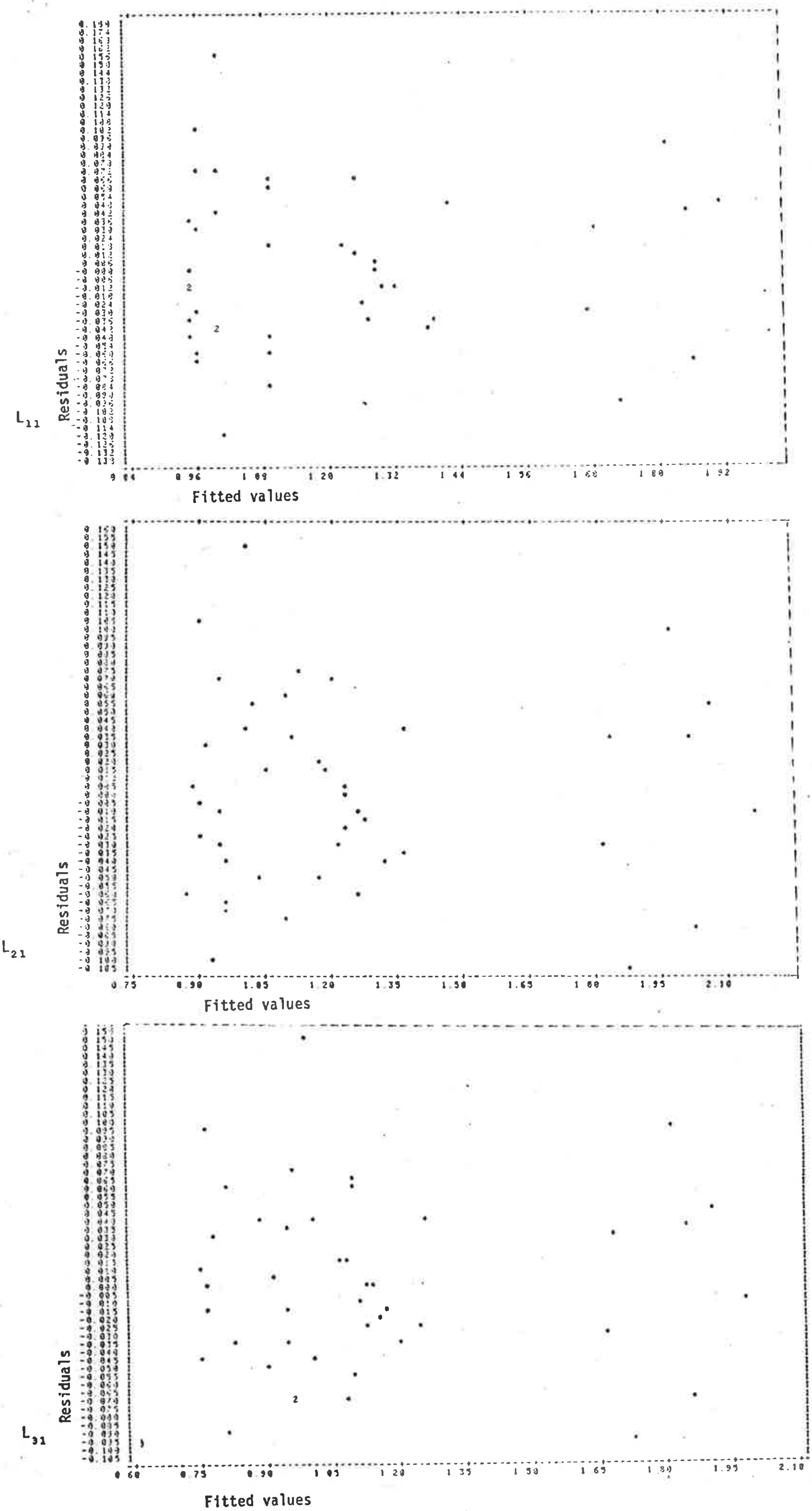


Fig. 4.1.1.11 Plot of residuals against fitted values of L_{11}, L_{21}, L_{31} of experiment 17 including sole crop treatments.

IV.1.2 THE CORRELATIONS OF THE TWO CROP YIELDS FOR ALL TREATMENTS IN INTERCROPPING EXPERIMENTS

1. INTRODUCTION

No quantity has been more characteristic of biometrical work than the correlation coefficient, and no method has been applied to such various data as the method of correlation (Fisher, 1921, 1970). When simple linear correlation coefficients between two variables are computed over several groups, it is desired to test the homogeneity of several correlation coefficients and obtain a single coefficient if they seem to be homogeneous (Steel and Torrie, 1960). For example, measurements on two characteristics of a crop or type of animal may be available from several strains or breeds. The strain or breed variances may not be homogeneous so that pooling sums of products and calculating a single correlation coefficient is not valid.

One of the popular methods for analysing the results of intercropping experiments is the bivariate approach described by Pearce and Gilliver (1978, 1979) and Gilliver and Pearce (1983) and set out in Section II.1.2 above. The method, however, requires the fundamental assumption that the correlations between two crop yields are constant for all treatments. By assuming the homogeneity of this correlation, their first method allows a transformation to give new variates with variance and covariance equal to one and zero respectively. In the second method, the correlation between two crops is allowed for by skew axes. However, Martin (in the discussion of Mead and Riley, 1981) emphasized that assumption of equal correlation between the two crop yields cannot be sustained, especially when crop density is varied.

Although equality of correlations between two crops for all treatments is important and simple to test, there are few studies testing that assumption as replication of each treatment is usually modest (Mead and Riley, 1981). This study is aimed to test the assumption by using per row data or plant samples as regarded as small plots from each plot for various kinds of intercropping experiments.

2. THE EXPERIMENT SAMPLES AND STATISTICAL ANALYSIS

2.1 The experiment samples

As noted earlier, most experiments have limited replication, so row data or plant sample data will be used here as small plots for testing the hypothesis of the equality of correlations between two crop yields for all treatments. Plant sample data are available from some of the Type 1 experiments and row data are available from the Type II experiments in Section III.2. The reason for using plant samples as small plots is that they can be seen in the physical layout of the experiments (Figs. III.2.1 to III.2.4 in Section III.2).

Results from plant sampling correspond to sole crop plots, but the plant samples are obviously much smaller. By considering the plant samples and the rows as small plots, we may compute correlations between two crop yields for all treatments with enough samples.

Although 6 samples are really too small for calculating the correlation coefficient, in this study we will still do so, using the plot basis data from experiments that have six replicates.

The experiments that will be used in this study are experiments 9, 11, 29, 32, 33, 37 and 38 for the plant samples, experiments 39, 40, 41 and 42 for the rows data and experiments 1, 5, 50 and 51 for the plot data, all as described in Section III.2.

2.2 Statistical Analysis

Fisher (1921, 1970) pointed out that with large samples and moderate or small correlations, the correlation obtained from a sample of n pairs of values is distributed normally about the true value ρ, with variance

$$\frac{(1 - \rho^2)^2}{n - 1} \quad . \qquad (4.1.2.1)$$

It is therefore usual to attach to an observed value r, a standard error $(1-r^2)/\sqrt{n-1}$, or $(1-r^2)/\sqrt{n}$. This procedure is only valid under restrictions stated above. However, with small samples as it is usual in practical research, the value of r is often very different from the true value, ρ, and the factor $1-r^2$, corresponding in error; in addition, the distribution of r is far from normal, so that tests of significance based on the large sample formula are often very deceptive. To overcome that problem, Fisher suggested transforming the value of r to z as

$$z = \tfrac{1}{2}[\ell n(1+r) - \ell n(1-r)] \qquad (4.1.2.2)$$

which is approximately normally distributed with approximate mean and standard deviation of $\frac{1}{2}\,\ell n(1+\rho)/(1-\rho)$ and $1/\sqrt{n-3}$ regardless of the value of ρ. Transforming r to z allows us also to test if two or more observed correlations are significantly different from each other. In other words, to test whether or not those observed correlations are homogeneous.

We illustrate this approach (i.e. testing for homogeneity of a set of correlation coefficients) by using the discussion of Steel and Torrie (1960) and Snedecor and Cochran (1980). Let $r_1, \ldots, r_k$ be k correlation coefficients based on samples of sizes $n_1, \ldots, n_k$. First convert the r_i to z_i, recording also the terms $(n_i - 3)$ for each z_i. Under H_0 the z_i are all estimates of the same mean μ but have different variances $\sigma_i^2 = 1/(n_i - 3)$. If the bias in mean z can be neglected, the test for homogeneity of the correlation coefficients is equivalent to the test of equality of the mean value of z (Rao, 1965). The test of significance is based on the result that if k normal deviates have the same mean μ but have different variances σ_i^2, the quantity

$$\sum_{i=1}^{k} W_i(z_i - \bar{z}_W)^2 = \sum_{i=1} W_i z_i^2 - \frac{\left(\sum_{i=1}^{k} W_i z_i\right)^2}{\sum_{i=1}^{k} W_i} \qquad (4.1.2.3)$$

is distributed as χ^2 with k - 1 degrees of freedom, where $W_i = 1/\sigma_i^2$ and $\bar{z}_w = \sum_{i=1}^{k} W_i z_i / \sum_{i=1}^{k} W_i$. In this application, $W_i = n_i - 3$ and

$$\chi^2 = \sum_{i=1}^{k} (n_i - 3) z_i^2 - \frac{[\sum_{i=1}^{k} (n_i - 3) z_i]^2}{\sum_{i=1}^{k} (n_i - 3)} \qquad (4.1.2.4)$$

We shall only consider single pairs of random variables, but more extensive analyses of correlation structure might be appropriate, using the results established by Rao (1979) and Brien (1980).

The analysis has all the limitations of any linear model, but can answer the simpler aspects of the problems raised by Martin (in discussion of Mead and Riley, 1981). Mead (1983) pointed out that in using plant samples or rows data, we assume that within plot variation is similar to between plot variation. Therefore, in this study we also test the homogeneity of correlation coefficients between plots in each treatment to examine the variation between and within plots.

3. RESULTS

As described in Section III.2, in general the experiments can be classified into two categories. The first type involved intercropping between staple food crops like maize, cassava or rice and legumes or other vegetable crops. The second type involved intercropping between sugar-cane as major crops and food crops or vegetable crops etc. as minor crops. It seems also interesting, first, to divide the result into two types as in Table 4.1.2.1. The χ^2 values indicate the homogeneity of correlation coefficients between two crop yields for all treatments in each experiment. From Table 4.1.2.1, it appears that 4 out of 9 experiments of experiment type I were not homogeneous in terms of their correlations. All the experiments of type II, however, show homogeneity of correlations for all treatments. Taking these results into consideration, it is interesting to examine in more detail, the mechanism of competition in terms of their correlations in each experiment.

Bearing in mind how few in number these experiments are, we will try to identify the relevant aspects of the structure of treatments in each experiment. In general, we can distinguish three types of experiments according to their treatment structure. The first one was experiments involving comparison of genotypes, the second one those involving fertilizer treatments and the third those involving density treatments.

Table 4.1.2.2 provides more detail on the treatment structure in genotype comparison experiment, in terms of their correlation coefficients between two crop yields. In all cases, the correlations were positive. The difference is of course only in the degree of mutual cooperation or competition, but at least the effects are all in the same direction for all treatments, although this result may not be true for genotypes that have major differences in canopy such as dwarf versus tall varieties. If we intercrop such genotypes with other crops that are sensitive to shading, then we may expect that with dwarf varieties mutual cooperation will occur, but competition will occur with tall varieties. Returning to Table 4.1.2.2, for experiment 29, it appears that treatment b and i seem to be different in their correlation coefficients; it could also be due to the land races.

The correlations between two crops in the experiments that involved fertilizer treatments are difficult to summarize, as can be seen from Table 4.1.2.3, which lists the correlation coefficients for each treatment in experiment 33. This experiment involved intercropping between cassava and peanut. The treatments were combinations between two different doses of fertilizer on peanut (A_i) and six different doses of fertilizer on cassava (B_j). From this table, the association between two crops between B_j treatments in A_1 and A_2 treatments are different, in respect of their correlation. With A_1 treatment (i.e. peanut without fertilizer) the competition between these two crops occurred at B_5 level and then increased as the level of fertilizer on cassava was increased. Cassava grows very rapidly and needs more other nutrients and also more light, and these factors may influence the growing of peanut. When peanut was fertilizer (i.e. within A_2), the competition occured from the B_1 to B_3 levels and as the levels of fertilizer on cassava (B_2) increased, the correlation became positive. It seems that giving nitrogen fertilizer on peanut may increase the requirement for another nutrient, competition occurring due to limiting levels of the other nutrient. The other correlation coefficients for this type of experiment can be seen in Table 4.1.2.4. It also appears that the association between two crops ranges from mutual cooperation to competition in each experiment. This result is not in any way surprising; as Pearce and Gilliver (1978) pointed out, that if more fertilizer is applied to a mixture of crops, in one respect the immediate effect may be to reduce competition, but later plants could become larger and there might then be more competition, even with respect to the nutrient elements supplied.

Table 4.1.2.5 lists the correlation coefficients of the two crops for experiments that involved density differences. As in experiments that involved fertilizer treatments, different patterns of association of the two crops occurred as revealed by their correlation coefficient. Experiment 1 is shown in more detail in Table 4.1.2.6, although the χ^2 test is not significant, very possibly primarily because the number of samples is too small. This experiment was aimed to assess the effect of four different proportions of peanut which are intercropped with cassava. Increasing peanut density at first stage was followed by increasing mutual cooperation, but this declined at 75% peanut and even competition at 100% peanut. Such a result can also be seen in experiment

37 (Table 4.1.2.7). The treatments were combinations of three different inter-row distances of maize (A_i) (i.e. 80 × 30, 160 × 30, 200 × 30cm) and five different leaf cutting times for the maize (B_j) (i.e. at 7 days, 12 days, 17 days, 20 days after silking and without leaf cutting). From Table 4.1.2.7, it appears that the effects of leaf cutting on the correlations of the two crops are much higher in high density (i.e. narrow inter row distance) than in low density. From this study, it appears that the association between two crops ranges from mutual cooperation to competition, though the increasing competition might simply be the result of increasing the density treatments.

The results of testing the homogeneity of correlation coefficients between plots in each treatment appear in Table 4.1.2.8 and 4.1.2.9. From these two tables, in general, the correlation coefficients between plot for each treatment are homogeneous. In other words, the patterns of within plot correlation is similar to that between plots. Hence, it should be reasonable to use the plant samples or rows for the analyses already described.

4. DISCUSSION AND SUMMARY

It is unlikely that equality of competition between two crops can hold exactly for all treatments, though in many instances it can be accepted as a reasonable approximation and no worse than the other assumptions made in applying statistical theory, e.g. that any treatment can be expected to have the same effect at all points in the experimental area or that all plots are equally subject to error (Pearce and Gilliver, 1978). From this study there were some experiments where one could accept that assumption. These experiments were classified as intercropping experiments that involved comparison of genotypes and also some of experiment II (i.e. intercropping of sugar-cane). There might be also some exceptions for genotype experiments that have different canopies (i.e. dwarf and tall varieties) if we intercrop with the other crops that are sensitive to shading. This result has also been indicated by Donald (1963), who emphasized that, although it is clear that competitive ability, in any particular set of circumstances, has a genetic basis, it is more difficult to accept the further proposition that such ability may be independent of those plant attributes giving competitive advantage for the factors needed for growth.

However, for intercropping experiments that involved fertilizer, insecticide, pesticide or herbicide treatments, the assumption of equal correlations between two crops for all treatments is difficult to accept. In the examples of such experiments examined here, the association between two crops varies from mutual cooperation to competition within a sample. This study also shows that in the experiments involving density treatments, the association also varies from mutual cooperation to competition. It appeared that at low density, mutual cooperation might have happened, but at high density competition took place. This result (i.e. the effect of densities) actually has also been discussed by Mather (1961). He emphasized that if the relationship is density independent, then it can only be neutral or cooperative, but if it is density dependent then there may be cooperation at low densities, followed by neutral relationship and finally be active competition as the density increases. As a result of this study, we may expect that the correlations between two crops in intercropping experiments will be much more complex if fertilizer and density treatments are involved together.

The χ^2 value is linear in $(n_i - 3)$ (Equation 4.1.2.4), i.e. the greater n_i, the greater the χ^2 values, and the power of the test is weak with the small sample size, as is well known (Snedecor and Cochran, 1980). Thus, in experiment 50 (Table 4.1.2.4), though the range of correlation coefficients is -0.547 to 0.423, and also experiment 1 (Table 4.1.2.6) with the range of -0.456 to 0.583, the results of the tests are not significant.

Although this study is based on small plots, so that the variability of data is greater, the result is a good indication of the validity of the assumption of equality of correlations between two crops for all treatments in intercropping experiments. The assumption is difficult to accept in experiments that involved fertilizer or density treatments, therefore in using the bivariate approach one should take great care. We recommend testing that assumption, first, though only on a sample basis. By having somewhat larger plant samples (i.e. at least three or four plants per sample) the result will be more reliable.

As noted earlier, using within plot variation to calculate the correlation coefficient requires that between and within plot patterns of variation for the two crops be similar. In most cases, the correlation coefficients between plot in each treatment are homogeneous. Therefore, it should be reasonable to assume the variation of the two crops with the same treatment within plot is similar to between plot and then use plant samples to calculate the correlation coefficient between those two crops. Of course, using plot values is much better and more appropriate, but there may not be experiments with ten or more replicates. Again, by having larger plant samples taken to reduce variability of the data, then calculating the coefficient correlation between two crops and testing the assumption of equal correlations for all treatments in intercropping systems will be more reliable.

TABLE 4.1.2.1 The χ^2 values for testing the homogeneity of correlation coefficients between two crop yields for all treatments in the intercropping experiments.

	Observed χ^2	Number of treatment	Number of samples
EXPERIMENT TYPE I			
Experiment 1	2.03	4	6
" 5	0.78	4	6
" 9	1.13	7	12
" 11	9.48	8	15
" 29	4.65	11	15
" 32	14.75*	7	20
" 33	32.50**	12	15
" 37	73.97**	15	40
" 38	87.33**	15	40
EXPERIMENT TYPE II			
Experiment 39	0.70	4	28
" 40	2.93	4	28
" 41	1.73	4	28
" 42	2.49	6	20
" 50	1.86	4	6
" 51	1.94	4	6

TABLE 4.1.2.2 The correlation coefficients between two crop yields for all treatments for experiments that were involved with genotype treatments.

	Treatments[a)]	correlation coefficients
Experiment 9	a	0.182
	b	0.210
	c	0.191
	d	0.405
	e	0.219
	f	0.113
	g	0.469
Experiment 29	a	0.429
	b	0.602
	c	0.555
	d	0.369
	e	0.342
	f	0.312
	g	0.173
	h	0.158
	i	0.084
	j	0.323
	k	0.148
Experiment 41	A_1B_1	0.649
	B_2	0.744
	A_2B_1	0.694
	B_2	0.810

a) See Section III.2 for details.

TABLE 4.1.2.3 The correlation coefficients between two crop yields for all treatments of experiment 33.

Treatments		
Fertilizer on peanut	Fertilizer on cassava	correlation coefficients
0 - 45 - 50[a] (A_1)	0 - 0 - 0 (B_1)	0.405
	0 - 30 - 60 (B_2)	0.675
	30 - 30 - 60 (B_3)	0.720
	60 - 30 - 60 (B_4)	0.420
	90 - 30 - 60 (B_5)	-0.243
	120 - 30 - 60 (B_6)	-0.570
225 - 45 - 50 (A_2)	0 - 0 - 0 (B_1)	-0.378
	0 - 30 - 60 (B_2)	-0.105
	30 - 30 - 60 (B_3)	-0.115
	60 - 30 - 60 (B_4)	0.226
	90 - 30 - 60 (B_5)	0.537
	120 - 30 - 60 (B_6)	0.434

a) - - - = doses of N, P_2O_5 and K_2O (kg/ha)

TABLE 4.1.2.4 The correlation coefficients between two crop yields for all treatments for experiments that were involved with fertilizer treatments.

	Treatments[a)]	correlation coefficients
Experiment 32	a	0.166
	b	0.187
	c	0.461
	d	0.582
	e	0.277
	f	0.067
	g	-0.488
Experiment 50	a	-0.547
	b	0.423
	c	0.168
	d	-0.101
Experiment 51	a	-0.746
	b	-0.094
	c	-0.748
	d	-0.240

a) See Section III.2 for details.

TABLE 4.1.2.5 The correlation coefficients of the two crop yields for all treatments of experiments that were involved with density treatments.

	Treatments[a)]	Correlation coefficients
Experiment 11	A_1B_1	-0.365
	B_2	-0.387
	B_3	-0.003
	B_4	0.262
	A_2B_1	0.182
	B_2	0.399
	B_3	0.353
	B_4	0.476
Experiment 38	A_1B_1	0.043
	B_2	-0.111
	B_3	-0.159
	B_4	-0.253
	B_5	-0.358
	A_2B_1	0.173
	B_2	-0.052
	B_3	-0.362
	B_4	-0.203
	B_5	-0.360
	A_3B_1	0.849
	B_2	0.272
	B_3	0.239
	B_4	0.209
	B_5	0.004
Experiment 39	A_1B_1	0.269
	B_2	0.333
	A_2B_1	0.402
	B_2	0.149
Experiment 40	A_1B_1	-0.474
	B_2	-0.199
	A_1B_1	-0.511
	B_2	-0.198
Experiment 42	A_1B_1	-0.083
	B_2	-0.008
	B_3	-0.077
	A_2B_1	-0.380
	B_2	-0.336
	B_3	-0.334

a) See Section III.2 for details.

TABLE 4.1.2.6 The correlation coefficients of two crop yields for all treatments of experiment 1.

Treatments	Correlation coefficients
Cassava (100%) + Peanut (25%)	0.012
Cassava (100%) + Peanut (50%)	0.583
Cassava (100%) + Peanut (75%)	0.094
Cassava (100%) + Peanut (100%)	-0.456

TABLE 4.1.2.7 The correlation coefficient of two crop yields for all treatments of experiment 37.

Treatments	correlation coefficients
A_1B_1	-0.149
B_2	-0.261
B_3	-0.508
B_4	-0.521
B_5	-0.577
A_2B_1	0.256
B_2	0.233
B_3	-0.148
B_4	-0.308
B_5	-0.428
A_3B_1	0.417
B_2	0.411
B_3	0.209
B_4	0.404
B_5	-0.091

TABLE 4.1.2.8 The χ^2 values for testing the homogeneity of correlation coefficients between plots in each treatment of experiment type I.

Experiment	Treatment	Observed χ^2	Number of plot
9	a	4.60	3
	b	3.76	3
	c	0.88	3
	d	0.16	3
	e	1.12	3
	f	3.27	3
	g	0.58	3
11	A_1B_1	2.07	3
	B_2	2.38	3
	B_3	0.30	3
	B_4	1.15	3
	A_2B_1	0.30	3
	B_2	0.43	3
	B_3	2.54	3
	B_4	2.94	3
32	a	21.36**	4
	b	5.19	4
	c	0.70	4
	d	1.44	4
	e	4.58	4
	f	3.17	4
	g	1.55	4
37	A_1B_1	12.52**	4
	B_2	2.38	4
	B_3	0.02	4
	B_4	2.57	4
	B_5	0.98	4
	A_2B_1	4.25	4
	B_2	10.26*	4
	B_3	3.08	4
	B_4	5.24	4
	B_5	1.12	4
	A_3B_1	1.33	4
	B_2	2.17	4
	B_3	8.51*	4
	B_4	3.22	4
	B_5	0.59	4
29	a	0.02	3
	b	1.75	3
	c	0.54	3
	d	0.50	3
	e	1.12	3
	f	0.16	3
	g	1.63	3
	h	0.42	3
	i	1.37	3
	j	1.20	3
	k	1.34	3
33	A_1B_1	3.13	3
	B_2	0.09	3
	B_3	0.70	3
	B_4	6.54*	3
	B_5	3.78	3
	B_6	0.95	3
	A_2B_1	4.49	3
	B_2	2.43	3
	B_3	7.93*	3
	B_4	6.45*	3
	B_5	0.15	3
	B_6	3.03	3
38	A_1B_1	1.93	4
	B_2	1.37	4
	B_3	1.04	4
	B_4	3.80	4
	B_5	5.43	4
	A_2B_1	6.28	4
	B_2	2.98	4
	B_3	5.52	4
	B_4	9.82*	4
	B_5	13.65**	4
	A_3B_1	3.86	4
	B_2	5.14	4
	B_3	11.08*	4
	B_4	2.91	4
	B_5	8.36*	4

TABLE 4.1.2.9 The χ^2 values for testing the homogeneity of correlation coefficients between plots in each treatment of experiment type II.

Experiment	Treatment	Observed χ^2	Number of plot
39	A_1B_1	1.60	4
	B_2	0.51	4
	A_2B_1	1.55	4
	B_2	1.53	4
	A_1B_1	2.23	4
	B_2	16.31**	4
	B_3	1.80	4
	A_2B_1	1.36	4
	B_2	0.77	4
	B_3	3.28	4
40	A_1B_1	10.10*	4
	B_2	5.14	4
	A_2B_1	4.83	4
	B_2	2.40	4
41	A_1B_1	1.76	4
	B_2	4.01	4
	A_2B_1	6.23	4
	B_2	0.61	4

IV.2. THE ASSESSMENT OF YIELD ADVANTAGES BY USING UNIVARIATE AND MULTIVARIATE ANALYSES

1. INTRODUCTION

While the yield advantages of intercropping systems seem very attractive, there are problems in assessing the degree of yield advantage (Mead and Willey, 1980). The assessment essentially is to determine whether an intercropping combination is better than sole cropping and whether, with combinations, one intercropping system is better than another. Part of the problem arose because of the differences in crops or because yields are difficult to compare. Therefore, it is generally appreciated that more than one analysis should be used in interpreting the intercropping data (Mead and Stern, 1979). Analyses on each crop yield separately and analysis of combined crops in some ways for intercropped plot yield have been recommended by Mead and Riley (1981).

As usual, when there are two different characteristics of interest, namely the yields of the first crop (A) and of the second crop (B), the estimation of the best treatment depends on what is meant by "best". One possibility is to say that higher yields of both crops are preferable to smaller ones, but then one does not know which of the pairs (20.34, 8.96) and (31.30, 2.97) is better because neither dominates the other in the sense of having larger yields of both crops simultaneously. The other possibility is to weigh the crops by a certain constant as monetary values or calorific values. In addition, however, it might be of interest to see the two crop yields as a response of the treatment effect as in bivariate analysis. As Willey (1979) emphasized that the purpose for conducting intercropping experiments may vary greatly in type of information required, thus the types of analyses will also vary. A study of Wijesinha, Federer, Carvalho and Portes (1982) showed that intercropping systems which aimed to maximize the yield of any one crop did not necessarily maximize total crop value or Land Equivalent Ratio. The other result obtained was that the multivariate analyses of variance for that experiment were in agreement with those from univariate analyses. This result may not be true in general.

The 51 experiments which have been considered in the present work, using the yield character of the crops, are mainly concentrated on assessing the degree of the yield advantages from the intercropping systems rather than on estimating the response of model equations. Therefore, the appropriate methods of response models that have been developed by Federer and his colleagues (Federer, Hedayat, Lowe and Raghavarao, 1976; Federer, 1979; Federer, Connigale, Rutger and Wijesinha, 1982), will not be included in this study. Furthermore, those methods are much more concerned with competition studies. As the experimenters have as their main interest the comparison between intercrop treatments (see later) then this work is also concentrated on the intercropping systems. The comparisons between sole crops and intercrops, if possible, is made by contrasting sole crop versus intercrop treatments.

This work attempts to examine various types of analyses on various types of intercropping experiments: the univariate analyses of each crop separately, the first crop yield equivalence by weighing of the relative price, the Land Equivalent Ratio and the multivariate analyses of variance and Pearce's and Gilliver's bivariate methods will be considered. The extension of the Land Equivalent Ratio with a new effective LER and the elaboration of the bivariate method are also considered.

2. STATISTICAL METHODS

Designs and analyses in both agriculture and statistics have been well developed for sole-cropped experiments, but are in a relatively primitive state for intercropping, or mixed cropping (Wijesinha _et al._, 1982). Even simple competition experiments need much development (Penfold Street, 1982). Testing hypotheses of constant means used the analysis of variance both in terms of univariate analysis and multivariate (bivariate) analysis.

2.1 Univariate analyses

A straightforward procedure, and one that is usually necessary to some degree, is to analyse the crops separately (Willey, 1979). This can be done using a reduced design which simply involves ignoring the sole treatments of the crop not under consideration. This is particularly useful for examining parameters which are only applicable to one of the crops. Analyses of variance are performed and appropriate F-ratios of means squares computed.

It can be seen in the description of experiments that the type of design used was either a Randomized Complete Block or Split Plot Design so that the basic linear model can be written as

$$Y_{ijk} = \mu + \omega_i + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \xi_{ijk} \qquad (4.2.2.1)$$

for a Randomized Complete Block Design where:

μ = the grand mean effect

ω_i = the effect of the i^{th} replicate

α_j = the effect of the j^{th} first factor

β_k = the effect of the k^{th} second factor

$(\alpha\beta)_{jk}$ = the interaction effect

ξ_{ijk} = the error term that $\sim N(0, \sigma^2)$

and

$$Y_{ijk} = \mu + \omega_i + \alpha_j + \omega(ij) + \beta_k + (\alpha\beta)_{jk} + \xi_{ijk} \qquad (4.2.2.2)$$

for a Split Plot Design where

ξ = the grand mean effect

ω_i = the effect of the i^{th} replicate

α_j = the effect of the j^{th} first factor as main treatment

$\omega(ij)$ = the whole plot error $\backsim N(0, \sigma^2_\omega)$

β_k = the effect of the k^{th} second factor as sub-plot treatment

$(\alpha\beta)_{jk}$ = the interaction effect

ξ_{ijk} = the split plot error $\backsim N(0, \sigma^2)$

As the available data did not include information on input costs (fertilizer, labor, seed, etc.) for the different monoculture and intercropping systems, to combine crop yields in terms of money, I consider the first crop yield equivalence as

$$Y_T = X_1 + X_2.C_2/C_1 \qquad (4.2.2.3)$$

where

Y_T = the first crop yield equivalence

X_1 = the yield of the first crop

X_2 = the yield of the second crop

C_1 = the price of the first crop at harvest time

C_2 = the price of the second crop at harvest time

The assumption made in this analysis was that the price of genotypes within a species involved in an experiment was the same. The analysis of variance was then carried out and F-ratios computed according to the appropriate models that have been described.

Another way of combining the two crop yields is to use the Land Equivalent Ratio as proposed by Willey (1979) and then extended by Mead and Willey (1980). The detailed methods have been described in Section II.1, so they will not be set out again. As I mentioned earlier in Section IV.1.1, although there was no consistent pattern over the six standardizations, I recommend using either L_{21} or L_{31} for easy calculation and reliability of comparison between the intercrop treatments (see later). To explain that argument, I consider only the average block standardization (i.e. L_{11}, L_{21}, and L_{31}) in calculating the LERs.

2.2. Multivariate analysis

Considering the first and second crop yield as joint variables, X_1 and X_2, a multivariate analysis of variance (Morrison, 1967; Mardia et al., 1980) and a bivariate analysis (Pearce and Gilliver, 1978, 1979; Gilliver and Pearce, 1983) were performed for comparison. The terms "multivariate" referring to standard MANOVA and "bivariate" referring to Pearce's and Gilliver's method will be used later.

Consider the two-way analysis of variance and suppose we have nrc independent observations generated by the model.

$$X_{ijk} = \mu + \alpha_i + \tau_j + \eta_{ij} + \xi_{ijk}, \quad i = 1, \ldots, r, \quad j = 1, \ldots, c, \quad k = 1, \ldots, n. \qquad (4.2.2.4)$$

where

α_i is the i^{th} "row" effect

τ_j is the j^{th} "column" effect

η_{ij} is the interaction effect between the i^{th} "row" and the j^{th} "column"

ξ_{ijk} is the error term $\sim N_p(\mathbf{0}, \boldsymbol{\varepsilon})$ for all i, j, k.

We require that the number of observations in each (i, j) cell should be the same, so that the total sum of squares and products matrix can be suitably decomposed. We are interested in testing the null hypotheses of equality of the α_i, equality of the τ_j, and the equality of the η_{ij}.

Let **T**, **R**, **C** and **E** be the total, rows, columns, and error SSP matrices, respectively. As in the univariate case, we can show that the following MANOVA identity holds, i.e.

$$\mathbf{T} = \mathbf{R} + \mathbf{C} + \mathbf{E} \qquad (4.2.2.5)$$

where

$$\mathbf{T} = \sum_{i=1}^{r} \sum_{j=1}^{c} \sum_{k=1}^{n} (X_{ijk} - \bar{X}_{...})(X_{ijk} - \bar{X}_{...})'$$

$$\mathbf{R} = cn \sum_{i=1}^{r} (\bar{X}_{i..} - \bar{X}_{...})(\bar{X}_{i..} - \bar{X}_{...})'$$

$$\mathbf{C} = rr \sum_{j=1}^{c} (\bar{X}_{.j.} - \bar{X}_{...})(\bar{X}_{.j.} - \bar{X}_{...})'$$

$$\mathbf{E} = \sum_{i=1}^{r} \sum_{j=1}^{c} \sum_{k=1}^{n} (X_{ijk} - \bar{X}_{i..} - \bar{X}_{.j.} + \bar{X}_{...})(X_{ijk} - \bar{X}_{i..} - \bar{X}_{.j.} + \bar{X}_{...})'$$

with

$$\bar{X}_{i..} = \frac{1}{cn} \sum_{j=1}^{c} \sum_{k=1}^{n} X_{ijk}, \quad X_{.j.} = \frac{1}{rr} \sum_{i=1}^{r} \sum_{k=1}^{n} X_{ijk}$$

and

$$\bar{X}_{...} = \frac{1}{rcn} \sum_{i=1}^{r} \sum_{j=1}^{c} \sum_{k=1}^{n} X_{ijk}$$

We may further decompose E into

$$\mathbf{E} = \mathbf{M} + \mathbf{W} \qquad (4.2.2.6)$$

where

$$\mathbf{M} = n \sum_{i=1}^{r} \sum_{j=1}^{c} (\bar{X}_{ij.} - \bar{X}_{i..} - \bar{X}_{.j.} + \bar{X}) + (X_{ij.} - \bar{X}_{i..} - \bar{X}_{.j.} + \bar{X}_{...})'$$

and

$$\mathbf{W} = \sum_{i=1}^{r} \sum_{j=1}^{c} \sum_{k=1}^{n} (X_{ijk} - \bar{X}_{ij.})(X_{ijk} - \bar{X}_{ij.})'$$

with

$$\bar{X}_{ij.} = \frac{1}{n} \sum_{k=1}^{n} X_{ijk}$$

Here **M** is the SSP matrix due to interaction and **W** is the residual SSP matrix. Thus from (5) and (6) we may partition τ into

$$\mathbf{T} = \mathbf{R} + \mathbf{C} + \mathbf{M} + \mathbf{W} \qquad (4.2.2.7)$$

under the hypothesis H_0 of all α_i, τ_j and η_{ij} being zero, $\mathbf{T}$ must follow the Wishart distribution,

$$Wp(\Sigma, rcn - 1)$$

Also, we can write

$$\mathbf{W} = \sum_{i=1}^{r} \sum_{j=1}^{c} \mathbf{A}_{ij}$$

say, and, whether or not H_0 holds, the $\mathbf{A}_{ij}$ are i.i.d. $Wp(\Sigma, n - 1)$.

Furthermore, as shown by

$$\mathbf{W} \sim Wp(\Sigma, rc\,(n - 1))$$

as in univariate analysis, whether or not the αs and τs vanish,

$$\mathbf{M} \sim Wp(\Sigma, (r - 1)(c - 1))$$

if the η_{ij} are equal.

It can be shown that the matrices **R**, **C**, **M** and **W** are distributed independently of one another, and further that the likelihood Ratio (LR) statistic for testing the equality of the interaction term is

$$|\mathbf{W}|/|\mathbf{W} + \mathbf{M}| = |\mathbf{W}|/|\mathbf{E}| \sim \Lambda(p, V_1, V_2) \qquad (4.2.2.8)$$

where

$$V_1 = rc(n - 1), \quad V_2 = (r - 1)(c - 1)$$

We reject the hypothesis of no interaction for low values of Λ.

Absence of an interaction effect implies that the row and column treatment tests must be made separately. The LR statistic to test the equality of the τ_j irrespective of the α_j and η_{ij} can be shown to be

$$|\mathbf{W}|/|\mathbf{W} + \mathbf{C}| \sim \Lambda(p, V_1, V_2) \qquad (4.2.2.9)$$

where

$$V_1 = rc(n - 1), \quad V_2 = c - 1$$

Instead of using the above test Rao (1948) transformed to the F-test. As described by Rao for two variables with any number of degrees of freedom of groups, the F test can be performed as

$$F = \frac{1 - \sqrt{\Lambda_{obs}}}{\sqrt{\Lambda}} \cdot \frac{n - g - 1}{g} \sim F(2g, 2(n - g - 1) \qquad (4.2.2.10)$$

where

Λ_{obs} = the Wilk lamda criterion

n = number of samples - 1

g = degrees of freedom of group.

The bivariate analysis of Pearce and Gilliver and details of this model have been described in the Literature Review (Chapter II.2) so will not be set out again in this Section.

3. RESULTS

1. Univariate Analysis

1. Analyses on each crop yield and the first crop equivalence

A preliminary analyses of variance was done separately on each crop yield. The analyses were performed only on experiments that have the same structure for both crops, so we can examine the same effects of treatments on each crop. Detailed investigation was carried out using the experiments 12 and 13, which differed only in the secondary crop.

In Tables 4.2.1 and 4.2.2, the analyses of variance on the maize and soybean yield of experiment 12 are shown. Different interpretations will arise according to whether maize yield or soybean yield is considered. Examining maize yield, by taking 5% significance level we can see that neither interaction effect nor genotypes of maize or soybean was significantly different (Table 4.2.1). In contrast, though the interaction effect was not significant, the effect of maize or soybean was significant as seen by analysing soybean yield. Sole maize yield and the maize yield of intercrop appeared not significantly different (Table 4.2.1.). In the maize-mung bean mixture (experiment 13), the analysis of maize gave a different result also (Table 4.2.3). From that table it also appeared that, even though the same genotypes were used as in experiment 12, the maize genotypes were significantly different when mixed with mungbean. From this result, it seems there are interactions between maize genotypes and the type of secondary crop and could be due to the site as well. This fact could be explained by comparing the treatment means of experiments 12 and 13 (Tables 4.2.1.8 and 4.2.1.9). Comparison of these two tables shows that in most cases the yield of maize in experiment 13 is higher than in experiment 12. Comparing Tables 4.2.3 and 4.2.4 shows different yielding interpretations. The effect of interaction was not significant, but either maize genotypes or mung bean genotypes were significantly different when analysis was based on mung bean yield.

The other results of analyses of each crop treated separately, including the two experiments that have just been discussed, are in Table 4.2.5. From that table, it appears that different conclusions arise from analysing each crop separately. Inspection of Table 4.2.5 also shows that neither peanut genotypes nor soybean genotypes nor mungbean genotypes nor upland rice genotypes significantly affected the maize yield. Taking this result into consideration, we might conclude then that the yield advantage of that system arises from the second crop yields. However, it is not so easy to maintain the full yield of the first crop by having different treatments on the second crop, as noted from experiment 13 and as may indeed be seen in Table 4.2.5 for all data sets. Comparisons between sole crop and intercrop yield of the first crop are given in Table 4.2.6. From this table, it appears that by using intercropping systems we might expect to get the same amount of the first crop yield as in sole crop. However, from Table 4.2.6, it also appears that some experiments showed different yields in the intercrop and sole crop systems. Inspection of Table 4.2.5 and 4.2.6 together reveals that to get the full yield of the first crop is not simply a matter of adding each sole crop population together to create an intercropping system. The additional treatments should be applied either to the first or second crop or both such as planting date, fertilizer, etc. Table 4.2.5 also reveals that the coefficient of variation varied between each crop in the same experiment and within each crop in different treatments. The treatments that are applied to the second crop not only affect the second crop but also can affect the first crop. It appears that intercrops of maize, and sweet potatoes or maize and upland rice yield the highest coefficient of variation on maize and also on the second crop. The intercrop of maize and mungbean showed less variability both on the yield of maize and mungbean.

In sugar-cane intercropping, the variability of sugar-cane was less than that of the second crop. Again, this result suggests that the variability of the first crop yield depends on the type of second crop and also on the type of treatments involved. The other result from those two tables is that though some experiments have extraordinary high coefficients of variation, they still show significant difference between treatments. Thus, there were quite large differences in the treatment means.

By interpreting the first crop and the second crop yields separately, the result might be different, because the two crops are not really independent (Table 4.2.21). From this result, considering the two crops as independent variates and interpreting the results separately on this basis might not be appropriate. Hence, we should combine the crops in some ways to compare intercropping treatments. Although monetary values can change and consequently the results of analyses also change, an economic index may be useful. By weighting the values of the second crop on the first crop, as considered in (4.2.2.3) the analysis of variance was done to all experiments (Table 4.2.7). That is one of the advantages of an economic analysis: all the crops can be combined linearly after weighting by price. However, there are also some disadvantages as mentioned earlier and will be illustrated in the bivariate methods. Detailed analyses of variance were performed using experiments 12 and 13 (Tables 4.2.8 and 4.2.9). It can be seen from Table 4.2.8 that the effects of intercropping systems were not significant, so it was possible to compare between yields of sole crops and intercropping systems. Sole maize and intercropping systems were significantly different, but sole soybean and intercropping were not. From this result two conclusion could be drawn. The first is that when crops are being grown primarily for subsistance, these farmers should grow intercrops rather than sole maize both for dietary requirements, and also to guard against risk and spread the labour peak. The second is that when crops are being grown for cash then farmers should grow sole soybean rather than intercrop soybean with maize. In fact, there is also a market problem in that, if all farmers grow soybean, then the price of soybean will drop and the price of maize increase. Hence, the maximum predicted return will not be obtained in practice. In the maize-mung bean intercrop (experiment 13), the result of analyses appear to be different from experiment 12 (Table 4.2.9). From that table, it appears that although maize genotypes were not significant, mung bean genotypes and its interactions were significantly different from zero. This result agrees with the different response of maize in respect to the secondary crops as indicated earlier in the analysis of each crop yield for those two experiments (Tables 4.2.1. and 4.2.3).

From the values of the coefficient of variation in Table 4.2.7, one sees that analysing the two crops combined is more stable than analysing them separately. The reduction in the first crop yield is compensated for by increasing the second crop or in constrast. Values of the means and the range of the first crop yield equivalence compared with the sole crop yield, calculated ignoring the treatment structure, are shown in Table 4.2.10. From Table 4.2.10, all of the intercropping systems showed more benefit than sole cropping, though some of them were not significantly different as in experiment 12, that have just been discussed. It also seems that a doubling of yield or more is obtainable from intercropping systems compared with sole cropping.

2. The Land Equivalent Ratio

Different conclusions can be obtained by analysing each crop separately, and analysis in terms of monetary returns will vary with the price of the two crops, so it is desirable to have the results in a form that can be applied in different situations, such as the LER. Interpretation of LER assumes that the largest simultaneous yield of the two crops is preferable to any smaller yield and, implicitly, that the yield proportions incorporated in that LER are those required by, or acceptable to, the farmer. As I mentioned earlier, although there are six possible standardizations for calculating LER values, I only consider three (i.e. L_{11}, L_{21} and L_{31}) for reasons which will become clear later. Detailed investigation was also carried out using experiments 12 and 13 (Tables 4.2.11 and 4.2.16). As the effect of intercropping systems in experiment 12 was not significant, both L_{11}, L_{21} and L_{31}, we can contrast between sole crops and intercropping systems. From Tables 4.2.11, 4.2.12 and 4.2.13, it seems that the result will be obtained in terms of L_{11} or L_{21} or L_{31}. This, however, was not always the case as in Tables 4.2.14, 4.2.14 and 4.2.16 for experiment 13. The other result of analyses including those two experiments appears in Table 4.2.17. Inspection of that table reveals that there were quite different results for L_{11}, L_{21} and L_{31}. In fact, the results of analyses using L_{21} and L_{31} are quite smaller. Returning to Section IV.1.1 on the coefficient of variation of LER, and comparing this with analysing each crop separately (Table 4.2.5), one sees that the analyses on the LERs are more stable. Again, as in the first crop yield equivalence result, the LERs take into account the compensation from both crops. The declining yield of the first crop is compensation for by the increasing yield of the second crop of vice versa.

It appears not only that the result of L_{11} analysis is different from L_{21} and L_{31}, but also that using L_{11} the treatment means are different (Table 4.2.1.8). Comparing the columns of L_{11}, L_{21} and L_{31}, the highest LER for L_{11} is not the highest one for L_{21} or L_{31} but the latter two yield the same result. In the treatments A_1B_2 and A_1B_3, though yield of both corn and soybean are higher for A_1B_2 than A_1B_3, the L_{11} of A_1B_2 is lower than A_1B_3, primarily because sole B_3 was so low. Obviously, the highest value of a ratio may be due not only to the magnitude of the numerator but also the smallness of the denominator. As this illustrates, having more than one divisor in calculating LER may give large discrepanices in comparison of the treatment means.

The mean and the range of L_{21} and L_{31} and the component LER of L_{31}, calculated without considering the differences of the treatment effects, are shown in Table 4.2.20. As the denominators of L_{31} are larger than those of L_{21} so the LERs that are calculated with L_{21} are larger than with L_{31}. Inspection of the means LERs suggests that, apart from experiment 22 that was damaged by mice before harvesting, all experiments have LERs larger than 1 for both L_{21} and L_{31}. It means that intercropping systems are better than sole cropping in terms of the efficient use of the land. Examining the maximum LERs, quite a lot of the intercropping systems are twice as efficient in using land (i.e. LER $\geqq$ 2.00), even with the maximum standardization (i.e. L_{31}). Inspection of L_{31} also shows that apart from experiment 22, most experiments have the LER $\geqq$ 1 (at least 75%). Again, intercropping systems are better than sole cropping in terms of using land. From Table 4.2.18, the means component LER of the first crop of the L_{31} standardization ranges from 0.39 - 1.19 and the component LER of the second crop ranges from 0.33 - 0.84 and most of them are ≧ 0.50. Inspection of the mean of the component LER of L_{31} also shows that in general, an increase in any one crop yield will be accompanied by a decrease in the other crop yields, though there are also some experiments with increased yield of both crops (i.e. both component LER > 0.50). Thus, either positive or negative association in the field can occur in the intercropping systems. If there is a positive association then choosing the highest LER will still be appropriate for the farmer's requirements as the highest LER will have the highest component LERs as well.

However, when the association between two crops is negative then the highest LER may have the highest component LER in any one crop but not for the other crops. In such a situation, the highest LER may not be desired by the farmer as he required a certain amount of the crop for staple food. Further results on how to interpret the LER will also appear in the bivariate analysis. Returning to Table 4.2.18 and examining intercropping, test factors and the LER total of the best treatment together, one sees that having a different planting date would yield the highest LER on maize and peanut intercrop. For the maize and soybean or maize and mungbean in the crops, combination of the appropriate maize and soybean genotypes or maize and mungbean genotypes yields a quite sustainable high LER (i.e. LER ≧ 2.00). Thus, even only by adding together of each sole crop to perform intercropping systems as in most experiments that did not involve population densities yield more efficiently in using land compared with sole crop. The important concern is how we should maintain the two crops with the same requirement but not at the same time or the different requirements at the same time. The limiting factors on each type of intercropping are of course different as shown by maize and peanut or maize and soybean and mungbean above.

2. Multivariate and bivariate analyses

As I mentioned earlier, because the multivariate analyses can only be conducted on crop combinations, no hypotheses related to comparisons with sole cropping can be tested. A multivariate or bivariate analysis of variance was performed on the vectors (X_{1i}, X_{2i}) for intercropping systems. X_{1i} denoted the first crop yield and X_{2i} the second crop yield. As in the univariate case, the necessary assumptions for the analyses are that the observations should be normally distributed and, very importantly, that the variance-covariance matrices of X_{1i} and X_{2i} should be the same for all populations. The results of Section IV.1.2 should be kept in mind; then assuming that the variance-covariance matrices are the same, test the hypotheses on the effects of the first and second crops as intercrops, and their interaction. The results are presented in Table 4.2.21. The results in that table suggest that the two analysis agree in terms of what effects they detect. In fact, these results are not in any way surprising since both tests were derived from the work of Wilk (1932). In the bivariate model, however, the test is simple and usually appropriate as most intercropping experiments involve only two variables. Therefore, only the bivariate methods will be discussed in more detail in a later section, using the relative graphical displacement of the treatment means. Inspection of the correlation of residuals suggested in general that both positive or negative values could occur. As Pearce and Gilliver (1978) emphasized, if the experimental soils are fertile it is to be expected that both crops will grow well, which makes a positive correlation for the two crops. However, since the two crops are in competition, this tends to make the correlation negative. It is possible that NN designs (Wilkinson, Eckert, Hancock and Mayo, 1983) will aid in resolving this problem, but no work has yet been carried out on this point. The other results from the correlation of residuals is that the two crops are in fact dependent, which explains the differences of the analyses of each crop yield separately. It can also be seen that the angle between two crops varies 58° to 120°, so that the angle of the two crops is not exactly 90°, as assumed in analysing each crop yield separately. Gilliver (in the discussion of Mead and Stern, 1979) also indicated that he quite often got the angles of the two crop yields up to 115°, and that is quite a considerable effect. Hence, considering the two crops as independent variates and analysing them separately will not be appropriate, but the two tests (i.e. analysis on the first and second crop yields separately) can be a useful complement to the multivariate or bivariate analysis. For example, as a result of the significance of the bivariate analysis, we could ask whether this is due to significant differences in first crop means, in second crop means or in both.

4. THE EXTENSION OF THE PREVIOUS METHODS

1. THE NEW EFFECTIVE LER

My original study of this new effective LER, was completed in April 1983, while Chetty and Reddy's paper appeared in 1984 with the model of the staple LER.

As I mentioned earlier, straightforward comparison of LER assumes that the largest simultaneous yield of the first crop (A) and of the second crop (B) is preferable. Also, as Mead and Willey (1980) emphasized, the yield proportions incorporated in that LER are implicitly those required by or acceptable to the farmer. Farmers may actually require a certain amount of crop A for staple food and some additional yield of crop B for a dietary need or for cash, so that the highest LER may not mean anything to the farmer, if his requirement of crop A is not met. In Section II.1, the effective LER of Mead and Stern (1979) and Mead and Willey (1980) was described. This takes into account the yield proportion of crop A desired by the farmer. They calculated this as the ratio $L_A/(L_A + L_B)$, i.e. L_A/LER total. It could be argued that the yield proportion of crop A required by the farmer also depends on the yield of crop B (i.e. L_B). The highest required yield proportion of crop A calculated by that method will not necessarily be the highest yield of crop A as well. Therefore, the required yield proportion of crop A does not mean the actual yield of crop A required by the farmer. In other words, the required proportion which is calculated by that method does not mean anything to the farmer.

Table 4.2.22 shows that the highest yield proportion of maize can be the lowest yield of maize, because the yield proportion of maize depends also on the yield of mung bean.

Table 4.2.22 The yield of maize and mung bean and the LER of some intercrop treatments of experiment 13.

Yield (kg/ha) corn	mung bean	The component LER L_C (maize)	L_M (mung bean)	LER Total	Proportion of maize $(L_C/(L_C + L_M)$
2700	1303	0.90	1.16	2.06	0.44
2283	788	0.76	0.70	1.46	0.52
2386	1016	0.80	0.90	1.70	0.47
2720	1038	0.91	0.92	1.83	0.50
2868	1101	0.96	0.98	1.94	0.49

Therefore, the farmer's requirement or required yield proportion of crop A is simply the yield of crop A or L_A itself in that intercropping. As an example, if the yield of corn required by the farmer is 2386 kg/ha then the required yield proportion of corn is simply $L_C = 0.80$.

As a result, of this modification of the required yield proportion, I simplified the concept of the effective LER, defining a new effective LER (i.e. LER'). As the concept of the new effective LER is the same as the effective LER, except the yield proportion required by the farmer, we may use the argument of Mead and Willey (1980). Considering the example in Table 4.2.23, Intercrop 2 (i.e. refers to Intercrop 4 in experiment 5) may be preferred by the farmer if the required yield proportion of rice is 0.73 instead of Intercrop 1 (i.e. refers to Intercrop 2 in experiments 5) though Intercrop 1 has a higher LER than Intercrop 2.

Table 4.2.23 The yield of rice and cassava and their LER in two different intercrops of experiment 5.

	Intercrop 1 yield (kg/ha)	LER	Intercrop 2 yield (kg/ha)	LER
rice	553	0.48	842	0.73
cassava	18489	1.08	10621	0.62
LER total		1.56		1.35
sole rice	1153			
sole cassava	17120			

Suppose the farmer required the yield proportion of rice to be $p' = 0.73$ (i.e. $L_{rice} = 0.73$ or 842kg of rice), but has in fact grown Intercrop 1 which gives an L_{rice} of only 0.48 (i.e. 533kg of rice). He could get his requirement by growing Intercrop 1 on part of his land and sole rice on the remainder (Mead and Stern, 1979). To consider how much extra sole rice would have to be grown with Intercrop 1, it is easiest to work out how much intercropping would be necessary on one hectare of land. Assume that a proportion of, k', of the land is grown with the Intercrop 1 and a proportion (1 - k') with sole rice.

The area of intercrop (k') for required proportion (p' = 0.75) is

$$0.73 = 0.48 \cdot k' + (1 - k')$$

$$k' = \frac{0.27}{0.52} = 0.52 \text{ ha}$$

and additional sole rice = (1 - 0.52)ha = 0.48 ha.

Hence, the new effective LER could be calculated as the biological efficiency of the system as follows:

	Yield (kg/ha)	LER	
From 0.52 ha of Intercrop 1			
cassava	9614	0.56	
rice	288 } 841	0.25 }	$p' = 0.73$
From 0.48 ha of sole rice			
rice	553	0.48	
new effective LER or LER'		1.29	

From the calculation of the new effective LER, if the yield proportion of rice required by the farmer is 0.73, then Intercrop 1 provides biological efficiency of only 1.29 compared with Intercrop 2 which gives 1.35. Again, by our definition of the required yield proportion (p') we will not only get the same proportion that is required (i.e. as Mead and Willey, 1979), but also get the yield of rice that is actually needed by the farmer, though the figures are not exactly the same, primarily due to the truncation of intercropping and additional sole rice area before calculation.

The calculation of the proportion of land for intercropping (k') for a required yield proportion (p') of crop A, in general is

$$k' = \frac{(1 - p')}{(1 - L_A)} \quad , \text{ if } p' > L_A \tag{4.2.4.1}$$

and

$$LER' = 1 + k'(LER - 1)$$

or

$$LER' = 1 + \frac{(1 - p')}{(1 - L_A)} \cdot (LER - 1) \quad . \tag{4.2.4.2}$$

If the required yield proportion of crop A is smaller than the actual yield proportion that was produced by that system (i.e. $p' < L_A$), then the proportion of land for intercropping (k') for a required yield proportion (p') of crop A is

$$k' = \frac{p'}{L_A} \quad , \text{ if } p' < L_A \tag{4.2.4.3}$$

and

$$LER' = 1 + \frac{p'}{L_A} \cdot (LER - 1) \quad . \tag{4.2.4.4}$$

The fundamental assumptions for this new effective LER are the same as those for the effective LER of Mead and Stern (1979) and Mead and Willey (1980), as noted in Section II.1.

From the comparisons of the treatment means of the LER, comparison between the intercrop treatments will not be reliable if we use more than one divisor in calculating LERs. However, there might be some interest in comparing intercrop treatments with each sole crop, as intercropping treatments at different nitrogen levels or herbicide levels, might be compared with sole crops at similar levels (Mead and Willey, 1980). In this situation, intercrop treatments have been standardized by each appropriate sole crop. If each component of a crop has been standardized by each sole crop treatment and we want to calculate the new effective LER, then the form of the calculation given earlier must be modified. The proportion of land for intercropping (k') for a required yield propotion of crop A (p' i.e. again p' has to be based on the maximum sole crop) becomes

$$k = \frac{(1 - p')}{(1 - C_A . L_{Ai})} \quad , \text{ if } p' > L_A \qquad (4.2.4.5)$$

where

$$C_A = \frac{S_{Ai}}{SA_{max}}$$

$$L_A = C_A . L_{Ai}$$

S_{Ai} = yield of sole crop of genotype i

SA_{max} = yield of maximum sole crop A

L_{Ai} = the land equivalent ratio of crop A under each sole treatment standardization

and

$$LER' = 1 + \frac{(1 - p')}{(1 - C_A . L_{Ai})} . ((C_A L_{Ai} + C_A . L_{Ai}) - 1) \qquad (4.2.4.6)$$

where

$$C_B = \frac{S_{Ai}}{S_{Amax}}$$

S_{Bi} = yield of sole crop B of genotype i

S_{Bmax} = yield of maximum sole crop B

L_{Bi} = the land equivalent ratio of crop B under each sole treatment standardization

and

$$k' = \frac{p'}{C_A.L_{Ai}} \text{ . if } p' < L_A \qquad (4.2.4.7)$$

$$LER' = 1 + \left(\frac{p'}{C_A.L_{Ai}}\right) . ((C_A.L_{Ai} + C_A.L_{Ai}) - 1) \qquad (4.2.4.8)$$

An Intersection between LER's

By plotting of the example in Table 4.2.23 as in Fig. 4.2.1, one can determine from the figure whether there is an intersection between LER's or not, on other words, find out the critical values p' of LERs between intercrop treatments. Thus, knowing p'_c (i.e. the critical values of required proportion), we can select a certain intercrop treatment that has the highest LER' of p'_c. Examination of Fig. 4.2.1 shows that the intersection between Intercrop 1 and 2 occurred between the lines of

$$LER'_1 = 1 + \frac{(1 - p')}{(1 - L_{A1})} . (LER_1 - 1)$$

and

$$LER'_2 = 1 + \frac{p'}{L_{A2}} . (LER_2 - 1).$$

Suppose

$$c_1 = \frac{(LER_1 - 1)}{(1 - L_{A1})}$$

$$c_2 = \frac{(LER_2 - 1)}{L_{A2}}$$

then the intersection of $LER'_1 = LER'_2$

i.e. $$1 + c_1(1 - p') = 1 + c_2 p'$$

$$p' = \frac{c_1}{c_1 + c_2}$$

or

$$p'_c = \frac{c_1}{c_1 + c_2} \qquad (4.2.4.9)$$

where p'_c is the intersection point of Intercrop 1 and 2, and it lies between $LA_1 \leq p'_c \leq LA_2$. If the maximum of LER' is too low, then we may not get an intersection point (i.e. p'_c is not in that interval). If it is in the interval, then lines intersect at p'_c as in (4.2.4.9) and at this point the biological efficiency of Intercrop 1 and 2 are the same, as assessed by the new effective LER (LER'). The LER'_1, however, is larger than LER'_2 at $p' < p'_c$ and in contrast when $p' > p'_c$. The LER' at p'_c (i. e. LER'_c) can be calculated either by LER'_1 or LER'_2

i.e. $$LER'_c = 1 + \frac{c_2 \cdot c_1}{c_1 + c_2}$$

or

$$LER'_c = 1 + c_1 \cdot \left[1 - \frac{c_1}{(c_1 + c_2)}\right] \quad . \qquad (4.2.4.10)$$

Suppose that LER'_1 is the highest one and $LA_1 > LA_2$ and the maximum of the other LER's are much lower than the maximum of LER'_1 then we may not get an intersection point. However, when the maxima of the other LER's are high enough then we may get an intersection point between these LER's. Therefore, the necessary conditions to get the intersection point in interval (L_{A_1}, L_{A_2}) has to be

$$\min(L_{A_1}, L_{A_2}) \leq \frac{c_1}{(c_1 + c_2)} \leq \max(L_{A_1}, L_{A_2}).$$

If it is true, then the lines intersect at p'_c as (4.2.4.9) and LER'_c as (4.2.4.10). By knowing that intersection we know the critical values of p' between two LER's and the range of p' of the intercrop system that gives the highest biological efficiency, i.e. we have in essence solved Mead and Willey's equation appropriately.

<u>Illustration of the method</u>

Let me illustrate this approach by using four of the experiments described in Section III.2.

In Fig. 4.2.2, the LERs for the four intercrop treatments (including the two treatments of experiment 5 that are used as an example in Table 4.2.23) are plotted against the required proportion (p') of upland rice. From the figure, it appears that delaying the planting of cassava increases the yield proportion of rice. Also from the figure, the calculation of intersection points must be between Intercrop 1 and 2 and Intercrop 2 and 4. The intersection points are $p'_{C12} = 0.44$ and $p'_{C24} = 0.69$ respectively. Thus, Intercrop 1 has the highest biological efficiency if the required yield proportion of rice is less than 0.44 and Intercrop 2 has the highest biological efficiency if $0.44 < p' < 0.69$ etc.

The same method of presentation is used with experiment 13 (Fig. 4.2.3). Here, A_1B_1 (i.e. the combination of maize cv. Harapan and mung bean No. 129) has the highest biological efficiency if the required yield proportion of maize is in the range $0.68 < p' < 0.91$ and A_2B_2 (i.e. the combination of maize cv. Kretek and mung bean TM. 106) has the highest biological efficiency if the required proportion of maize is greater than 0.91. The other examples are shown in Fig. 4.2.4 (experiment 6) and Fig. 4.2.5 (experiment 19). These two results are a bit different from the previous ones. The highest LERs from these two experiments also have the highest proportion of maize as well. Intercrop 6 (i.e. in experiment 6 as in Fig. 4.2.4) has the highest biological efficiency for $p' > 0.43$. On the other hand, in Fig. 4.2.5, it can be seen that Intercrop 1 (i.e. A_1B_1 of experiment 19) has the highest new effective LER whatever the required yield proportion of maize.

The general conclusion from these four experiments is that again, the intercropping systems are more beneficial than sole cropping in terms of the efficient use of land, even with the maximum sole crop standardization. In addition, the maximum land efficiency can be obtained even when the required yield proportion (p') is larger than 50%. Hence, if the yield of crop A required by the farmer is at least 0.50, then the maximum efficiency of land use can be achieved by growing Intercrop A and B rather than dividing his land into two parts and growing A and B separately.

Remarks on the Method

As a measure of biological efficiency in intercropping experiments in terms of the use of land, the new effective LER has the following features:

(a) As we restrict the interval of the required yield proportion of crop A to be 0 to 1, then those formulae all exist for $L_A \leqq 1$. The maximum L_A in most cases is 1; it means we only grow sole crop A. If the farmers require crop A and some additional crop B, then they grow the intercrop of crop A and crop B, and if they get $L_A \geqq 1$ they will get less of crop B. Therefore, the required yield for that situation is for crop B and crop B could be more economical, requiring only replacement of L_A by L_B or L_B by L_A.

(b) As we simplify the required yield proportion (p') of crop A with the new effective LER (LER'), the interpretations are also simple and more appropriate to the practical situation. For example, if the yield of rice required by the farmer is 576 kg per hectare then p' is simply the same as L_{rice} = 0.50 (from the fifth experiment). Furthermore, LERs are linear in p', so drawing of LERs against p' is simply the connection between the two p' values (i.e. p' = 0 and p' = 1) with the maximum LERs of that system as equal to LER.

2. THE GRAPHICAL PRESENTATION AND THE ELABORATIONS OF THE BIVARIATE METHODS

The importance of bivariate methods for analysis of intercropping experiments is that intercropping data are essentially multivariate and it is unlikely that those crops are independent (Pearce, in the discussion of Mead and Riley, 1981). Although these methods have been available since 1978 (Pearce and Gilliver, 1978; 1979 and Gilliver and Pearce, 1983), they have so far been little used (Dear and Mead, 1983). Part of the problem as in many multivariate analyses, is the emphasis on testing of hypotheses, rather than estimation of the treatment means.

Assuming the variance-covariance matrices of X_1 and X_2 are the same, and transforming to uncorrelated pairs of variables Y_1 and Y_2 or Z_1 and Z_2, Pearce and Gilliver (1978, 1979) and Gilliver and Pearce (1983) proposed the simple procedure based on graphical displacement for testing treatment means which was described in Section II.2. The transformed variables Y_1 and Y_2 can be graphed in the usual way as they are independent and also Z_1 and Z_2 by allowing for the correlation of those two variables. They also pointed out how the graphs can also be used to display the straight lines representing equal monetary or calorific values as in formulae 2.1.2.14. As the graph is in terms of Y_1 and Y_2 or Z_1 and Z_2, it is easier to work on units of Y_1 and Y_2 or Z_1 and Z_2 instead of X_1 and X_2. Suppose a unit of Y_1 is held to be worth α_1' and the unit of Y_2 is valued at α_2', then

$$c = \alpha_1' Y_1 + \alpha_2' Y_2 \quad . \qquad (4.2.4.11)$$

From the previous transformations (2.1.2.4) and (2.1.2.5) we know that

$$X_1 = Y_1 \sqrt{V_{11}}$$

$$X_2 = Y_2 \sqrt{V'_{22}} + \frac{V_{12}}{V_{11}} X_1 = Y_2 \sqrt{V'_{22}} + Y_1 \frac{V_{12}}{\sqrt{V_{11}}}$$

then

$$c = \left[\alpha_1 \sqrt{V_{11}} + \alpha_2 \frac{V_{12}}{\sqrt{V_{11}}} \right] . \; Y_1 + \alpha_2 \sqrt{V'_{22}} \; . \; Y_2$$

so

$$\alpha_1' = \frac{\alpha_1 V_{11} + \alpha_2 V_{12}}{\sqrt{V_{11}}} \qquad (4.2.4.12)$$

$$\alpha_2' = \alpha_2\sqrt{V_{22}'} \qquad (4.2.4.13)$$

and two points are

(a) $Y_1 = 0$, then $Y_2 = c/\alpha_2'$ (4.2.4.14)

(b) $Y_2 = 0$, then $Y_1 = c/\alpha_1'$. (4.2.4.15)

Drawing the lines of equal monetary or calorific value, then one is simply connecting the two points (4.2.4.14) and (4.2.4.15) on the axes of Y_1 and Y_2 respectively.

Lines of equal value can also be used to represent the contour lines having the same value of the Land Equivalent Ratio, which is

$$c = \alpha_1'' L_A + \alpha_2'' L_B \qquad (4.2.4.16)$$

Suppose that S_A and S_B are the maximum or the average yields of sole crop A and B respectively, then analysing in terms of X_1 and X_2 or in L_A and L_B (i.e. $\frac{X_1}{S_A}$ and $\frac{X_2}{S_B}$) , the result of the test and also the graph of Y_1 and Y_2 are exactly the same. The difference is of course in the variance-covariance matrices of X_1 and X_2 and L_A and L_B. Let us suppose that V_{11}'', V_{22}'' and V_{12}'' are the variance-covariance matrices of L_A and L_B, then

$$V_{11}'' = V_{11}/S_A^{\,2}$$

$$V_{22}'' = V_{22}/S_B^{\,2}$$

$$V_{12}'' = V_{12}/S_A . S_B$$

and

$$\alpha_1'' = \left(\frac{V_{11}}{S_A} + \frac{V_{12}}{S_B}\right)/\sqrt{V_{11}} \qquad (4.2.4.17)$$

$$\alpha_2'' = \sqrt{\frac{V_{22} - V_{12}^2/V_{11}}{S_B^2}} \qquad (4.2.4.18)$$

As in the LER, we ignore the relative values of each crop (i.e. α_1 and α_2 are equal to 1), then the two points are the same as (4.2.4.14) and (4.2.4.15) by substitution of α_1' and α_2' with α_1'' and α_2'' respectively.

The use of bivariate methods for combining two experiments will be discussed in the stability analyses, so will not be described here. Detailed graphical presentation of the method will be illustrated by using experiments 1, 5 and 13; and experiments 19 for illustrating the bivariate interaction. As the two transformations (i.e. Y_1 and Y_2 or Z_1 and Z_2) yield the same result, only Y_1 and Y_2 wil be examined, as it is easy to graph on orthogonal axes.

The bivariate analysis provides three results, analysis of first crop and second crop yields separately and the joint analysis of both crop yields. It appears from Table 4.2.21 that the effects of peanut densities of experiment 1 and time of planting of cassava of experiment 5 are significant so the results can be plotted as in Fig. 4.2.6 and 4.2.7. The circles shown for each mean are those which include all other mean points not significantly different at the 5% level. From Fig. 4.2.6, the peanut densities followed by increasing yield of peanut, but does not much reduce cassava yield as the effect of peanut densities on cassava yield is not significant (Table 4.2.5). The four treatments can be clearly distinguished in Fig. 4.2.6. As the cassava yields are not significantly different, we take treatment 4 (i.e. cassava + 100% of peanut) as the best treatment. The lines of equal yield of cassava equivalence and the LER also support this conclusion. From Fig. 4.2.7, delaying cassava planting increases the yield of rice, but decreases the yield of cassava; it also appears from Table 5 that the time of cassava planting affected both cassava and rice yield. Monetary value analysis would yield different answers according to the relative prices of rice and cassava (Fig. 4.2.7). At a ratio of 7 in the prices of those two crops at harvest time, treatment 1 is the best and treatment 4 the worst in terms of cassava yield equivalence. However, at the ratio of 19, the highest cassava yield equivalence appears to be treatment 4.

Clearly, analysing in terms of money or first crop yield equivalence is not always appropriate for the next season or year. The lines representing equal LER, however, will not change, so LER will be a more useful metric than monetary value.

The other illustration of the bivariate graphical method appears in Fig. 4.2.8 of experiment 13. As the model is no longer additive, as shown by the significance of the interaction effect (Table 4.2.21), we should interpret the results in terms of treatment combinations. Fig. 4.2.10 shows the mean yield pairs for 12 maize and mung bean genotype combinations. The circles also shown for each mean are those while include all other mean points not significantly different at the 5% level. It appears that A_1B_1 (i.e. maize cv. Harapan and mung bean No. 129) gives the highest yield of mung bean, but it is not significantly different from A_2B_2. (A_1B_2 is higher in terms of mung bean yield than A_2B_2 but lower in maize yield and clearly significantly different from either A_1B_1 or A_2B_2.) Thus, the combination A_1B_1 is better than the others if we can regard reduced maize yield as less important than increased yield of mung bean. However, as the two crops are different both of in value and in use by the farmer, the result may not be appropriate. As illustrated in experiment 1 (Fig. 4.2.6), experiment 5 (Fig. 4.2.7) and noted earlier, this method is useful in testing, but not in estimating the best treatment. As in experiment 5 (Fig. 4.2.7) for experiment 13, the straight line representing the equal maize yield equivalance and the LER are shown in Fig. 4.2.9. From that figure, the A_1B_1 combination shows the highest benefit in terms of maize yield equivalence. However, this result may not always be as in that Fig. 4.2.9, when the prices of the two crops change. In Fig. 4.2.10, the different ratio of the price of maize and mung bean gives different slopes for the lines of equal maize yield equivalence. As a result, as noted earlier in experiment 5, the treatment regarded as best will vary with the ratio of the price of the two crops involved. Clearly, use of the economic value may not always be appropriate. Therefore, it is desirable to have a method that can be applied in most situations, such as the LER. In using LER as an index, we should remember that the two crops do not mean the same to the farmer as to the researcher. Therefore, in interpreting the LER, we should not only consider the LER total itself, but also its component. Returning to Fig. 4.2.2, (i.e. Section IV.2.4.1), we see that the highest LER total does not also have the highest yield proportion of rice (i.e. L_{rice}), while in Fig. 4.2.9, the highest LER does not also have the highest yield proportion of maize. Therefore, if the farmer's requirement of rice or maize for staple food is not fulfilled, he disregards the highest LER. Displaying the results in the bivariate graphs clearly gives us the magnitude of LER total as a function of the component LERs.

The bivariate plot of the data can also be seen as representing interaction more clearly than a tabulation of the data. From Table 4.2.21, only one of the two by two factorial experiments shows significant interaction: experiment 19. This experiment involved two genotypes of maize (i.e. maize cv. Harapan and cv. Kretek) combined with two different population densities of maize (i.e. 60,000 plants or 90,000 plants per hectare) intercropped with peanut cv. Gajah. The graphical display of the interaction in experiment 19 can be seen in Fig. 4.2.11. Four points are clearly distinguishable. At low densities, the maize cv. Kretek (A_2B_1) gives much higher peanut yield compared with maize cv. Harapan (A_1B_1). However, when the population densities increase, the yield of peanut greatly decreases and only a small increase in the yield of maize occurs (A_2B_2). Maize cv. Harapan shows a different response, where at high density the maize yield is greatly increased, but the decline in peanut yield is not so large. This result shows how the response of the treatments can also be seen clearly in the bivariate plot. The method will also be useful in displaying the different doses of fertilizer in different types of elements or in insecticide or herbicide experiments.

5. DISCUSSION AND SUMMARY

So many analyses have been done on intercropping experiments that some divergent conclusion will not be surprising. From the results of the first analyses on separate crop yields, different interpretations could be obtained. For example, in experiment 12 the different interpretation could be obtained by analysing maize and soybean yields separately. This fact can also be seen in experiment 13 by analysing maize and mung bean yields separately. Returning to Section III.2, suppose a farmer is only interested in the first crop yield due to his requirement of staple food or from the second type of experiment that the factories are only interested in sugar-cane yield, then we should concentrate on keeping full yield of the first crop. By analysing the first crop yield and supposing the intercroppings were not significantly different, one would find that the advantages of intercropping simply arise from the second crop yield. However, keeping full yield of the first crop is not a simple matter. From the analyses of each crop yield separately, despite intercrop systems not being significantly different in first crop yield, in at least 50% of cases intercropping yields differed significantly from sole crop yields. Furthermore, interpretation in terms of each separate crop yield is much more difficult, when there are significant differences. The different result obtained from each crop separately can be examined by looking at the correlation between the two crops in each experiments, for example by multivariate and bivariate analyses. The two crops are not completely independent, but later more can be said.

The other weakness of analysing each crop separately lies in the fact that a farmer uses a combination of both yields for obtaining food or profit. He does not consider the yields separately, but rather total yield of both crops, a subjective performance index. Therefore, an analysis of combined yield in some form should be carried out for completeness.

Before discussing the other types of analyses, consider the structure of sole crop in each experiment (Table 4.2.24). Only 43% of experiments have complete sole crop treatments, 23% of sole crops as treatments and 20% as control treatments. The characteristics of the second type of experiment have been clarified by the presence of a control of sugar-cane. It seems that most experimenters are sure that intercropping will give much more benefit than sole cropping, so that it is not necessary to compare between sole crop and intercropping systems. Hence, I mainly concentrate on the intercropping systems, though in some cases, I also consider the comparison of sole crop and intercrop systems.

Combining yields in terms of money or in this study, first crop yield equivalence, is the easiest method of mixed crop analysis to interpret. All types of crops can be weighted by their price in terms of linear models. Therefore, there is no type of experiment that cannot be combined and the result is also easy to interpret both to the farmer or the researcher. The results of analyses in terms of first crop yield equivalence also showed that intercropping systems were better than sole cropping. As we combine the yields, the two crops compensate for each other, so that the coefficient of variation of the first crop yield equivalence is lower than for each separate crop yield. Though this type of analysis is easy to perform and to interpret, the result will change according to the market situation, as the prices of those two crops vary. This can be seen in the bivariate method of straight lines representing equality of the first crop yield equivalence. As the slopes of the lines move according to the ratio of the prices, then the maximum return or the maximum first crop yield equivalence will change. If the experience of ten years or more suggests that the fluctuations of the ratio of crop prices are not so large, then a researcher may give a recommendation to farmers to grow a certain intercrop combination that gives the maximum expected return at harvest time. If farmers follow the recommendation and all grow the same crops, then the prices of those two crops will drop and the prices of the crops that are urgently required will increase at the next harvest time. In fact, in East Java in 1979, the average price of rice varied between \$0.01 to \$0.40 per kg, the price of maize varied between \$0.07 to \$0.15 per kg and the price of cassava varied between \$0.01 to \$0.06 per kg (Anonymous, 1979). In the Philippines, Gomez and Gomez (1983) mention that the price of tomatoes varies between \$0.09 to \$0.79 per kg. The fluctuation will be even larger if everyone produces the same crops at the same time and requires the other crops. Thus, use of monetary value of assessing intercrops is subject to uncertainty which cannot be allowed for statistically.

Therefore, we require an index that will not change in these circumstances, such as the Land Equivalent Ratio (LER). By using this index, as I mentioned earlier, straightforward comparison of LER assumes that the largest yield of crop A and crop B simultaneously is preferable. Also, the component crop yields incorporated in the LER are those required by the farmers (Mead and Willey, 1980). This index is not easy to interpret from the farmer's point of view, as they have a certain requirement of the first crop for staple food and some of the second crop for dietary requirements or for cash. Therefore, use of the new effective LER is more appropriate than LER itself. By considering the required yield proportion, we can calculate the highest biological efficiency in terms of the new effective LER. I believe this model is much more useful in interpreting the results of intercropping experiments compared with the maximum return concept. The criticism of the new effective LER is contained in the question, why should we work on the required yield proportion and not on the maximum return concept? If the farmer considers the maximum return then he can buy the staple crop for food.

Again, the problem is which treatments have the maximum return. Of course, this depends on the price situation. Hence, I believe that the concept of the new effective LER is more appropriate to satisfy both the farmers and the researchers.

As I have illustrated, in the Land Equivalent Ratio analyses, and also Mead and Willey (1980) emphasized, having more than one divisor in calculating LERs can make the results unreliable for comparing the intercropping systems. The standardization by each sole crop treatment is appropriate only for comparing a particular intercropping treatment with the appropriate sole crop, and not for comparing between intercrop treatments. Most researchers have excluded sole crops from their experiment, so we may use only one divisor in each component crop yield, either the average sole crop yield or more appropriately, the maximum sole crop yield. The aim of intercropping experiments is to get the maximum combined yield and to ensure that in some sense this exceeded the maximum sole crop yield. Therefore, we return to the different concept of the Land Equivalent Ratio (Willey, 1979) and the Relative Yield Total (de Wit, 1960; de Wit and van den Bergh, 1965; and van den Bergh, 1968). The sole crops for calculation of the Relative Yield Total are necessarily from a replacement series experiment and not from other experiments (Spitter, 1983), but Willey and Osiru (1972), Huxley and Maingu (1978) and Willey (1979) pointed out that the competition in the intercropping systems is different from that in sole crop situations, so that we should not calculate the LER based on the sole crop at the same proportion in the Relative Yield Total. The maximum achievable sole crop yield may be more appropriate as the LER denominator (Huxley and Maingu, 1978). Returning to the unavailability of sole crops, if the researchers knew the maximum sole crop yield of a particular system in a given site, then they might calculate the LERs and also use the new effective LER. If the researchers want to estimate sole crop yields more precisely, then they may include the sole crops in their experiment, but not in their randomized layout. The plots could be larger than intercropping plots, but the replications could be fewer. Using this criterion of denominators for LERs, the calculation is easy and the result also much more appropriate in comparison between intercropping systems.

By combining the crop yield in terms of the first crop yield equivalence or the LER, we ignore the response of each crop yield to the different treatments. The multivariate or bivariate methods takes into account each crop yield as a response to the treatments. If two crops are not really independent, then in the bivariate method this is seen in the displacement of the treatment means. As in multivariate analyses, the bivariate method is useful in testing of hypotheses, but not in estimation of the treatment means. From this point of view, Finney (1956) strongly contested the usefulness of multivariate analyses of variance in agricultural context. By combining the two crop yields in terms of money or LER, we can select the best treatment on certain assumptions. The monetary analysis assumes the price of those two crops is fixed, which in fact is not true or yields a range of answers from a range of assumptions about price, while the LER assumes that the largest simultaneous yield of the two crops is preferable to smaller ones. The other important feature of bivariate methods is that by using the component LERs, we can use not only the LER total but also the component LERs. In the LER total, we do not know which of the crop dominates the LER total as the two crops meet different requirements of the farmer. As the study of Wijesinha et al. (1982) also showed, an intercropping system which aimed to get a full yield of any one crop did not necessarily maximise the combined yield as well. As a result, people often argue that in using LER index, the highest LER sometimes does not mean anything to the farmers. My study shows that in using LERs as an index of yield advantage, we should not only consider the LER itself, but also its components. By displaying the components on those two axes (i.e. bivariate method) then we can examine the magnitude of the LER total as a function of the component LER from the response to the treatments.

For all the reasons given, I suggest the new effective LER as an alternative criterion of the best treatment, defined as that which has the yield of the main crop meeting the farmer's requirements and the highest biological efficiency (LER') as well. Again, I believe that this concept is useful in interpretation of the yield advantages from intercroppping systems. By having the general criterion of the yield proportion of the main crop required by the farmers (say at least 60% or 70% from sole crop) or 90% of sugar-cane required by the factories, then we can work on the intercropping systems which give the highest new effective LER. Although the intercropping systems which aimed to get a full yield of the main crop did not necessarily maximise the combined crop yield in some ways, this requirement is not easy to maintain. Therefore, this new effective LER concept offers to solve that problem by taking into account the yield requirement of the farmer.

TABLE 4.2.1 Analysis of variance of the maize yield of experiment 12

SOURCE OF VARIATIONS	DF	MEAN SQUARE
Block	2	1.6121
Intercropping systems		
maize genotypes	1	0.0217
soybean genotypes	5	0.2940
interactions	5	0.2931
Error	22	0.3392
Sole maize vs intercrop	1	0.280

TABLE 4.2.2 Analysis of variance of the soybean yield of experiment 12

SOURCE OF VARIATIONS	DF	MEAN SQUARE
Block	2	0.6192
Intercropping systems		
maize genotypes	1	0.2404*[a)]
soybean genotypes	5	0.2351**
interactions	5	0.0665
Error	22	0.0505

a) * = significant at 5% level
** = significant at 1% level

These signs (i.e. * and **) will be used in the later tables with the same meaning.

TABLE 4.2.3 Analysis of variance of the maize yield of experiment 13

SOURCE OF VARIATIONS	DF	MEAN SQUARE
Block	2	1.5482
Intercropping systems	11	
maize genotypes	1	6.3755 **
mung bean genotypes	5	0.5155
interactions	5	1.4358
Error	22	0.6544

TABLE 4.2.4 Analysis of variance of the mung bean yield of experiment 13

SOURCE OF VARIATIONS	DF	MEAN SQUARE
Block	2	0.2701
Intercropping systems	11	
maize genotypes	1	1.4572 **
mung bean genotypes	5	8.8913 **
interactions	5	0.1555
Error	22	0.0852

TABLE 4.2.5. Analysis of variance of the first crop and second crop yield separately.

No. of Expt.	Intercropping	Test factors	1st crop The F-ratio of Main factors	1st crop The F-ratio of Interactions	CV(%)	2nd crop The F-ratio of Main factors	2nd crop The F-ratio of Interactions	CV(%)
7	Maize & Peanut	Nitrogen on maize + peanut	77.82**		14.86	32.73**		2.99
17	" "	Planting date of maize + peanut	53.91**		5.56	218.33**		4.61
25	" "	Peanut genotypes	0.30		26.40	2.17		16.06
6	" "	Nitrogen on maize	99.15**	} 1.45	17.83	17.83**	} 0.55	10.40
		Population of maize	14.60**			0.29		
15	" "	Population of maize	52.50**		18.14	0.06		28.23
18	" "	Planting date of maize	6.46**	} 0.75	11.40	33.60**	} 0.11	10.20
		Population of maize	137.83**			3.17		
19	" "	Maize genotypes	6.99*	} 112.74**	6.22	49.90**	} 17.00	4.64
		Population of maize	34.77**			137.08**		
20	" "	Maize genotypes	72.25**	} 0.59	10.67	0.74	} 0.27	29.06
		Population of maize	97.23**			11.72**		
9	Maize & Soybean	Soybean genotypes	1.48		15.00	6.28**		14.30
29	" "	Soybean genotypes	1.02		32.77	3.42*		36.73
32	" "	Nitrogen on maize	23.48**		14.26	3.64*		15.12
10	" "	Direction of rows planting	1.32	} 4.00**	11.50	1.33	} 0.08	30.39
		Within row distance of maize	2.62			0.50		
11	" "	Direction of rows planting	7.43*	} 0.91	15.87	1.15	} 0.11	16.29
		Within row distance of maize	0.85			0.62		
12	" "	Maize genotypes	0.06	} 0.86	21.41	4.76*	} 1.32	18.14
		Soybean genotypes	0.87	} 0.52		4.66**	} 0.06	
		Planting distance of maize	3.43			0.64		
22	" "	Maize genotypes	8.56**	} 0.81	7.60	20.88**	} 1.46	26.80
		Leaf cutting of corn	65.44**			1.29		
23	" "	Maize genotypes	8.04**	} 1.06	12.00	0.30	} 0.87	12.20
		Leaf cutting of corn	10.78**			0.21		
31	" "	Maize genotypes	0.22	} 1.89	22.38	0.23	} 0.73	14.78
		Population of maize	14.34**			0.33		
8	Maize & Mungbean	Mung bean genotypes	0.96		16.70	145.52**		3.60
13	" "	Maize genotypes	9.74**	} 2.19	13.77	17.10**	} 1.83	12.57
		Mungbean genotypes	0.79			104.36**		
14	" "	Maize genotypes	55.79**	} 0.11	13.77	1.11	} 1.12	19.72
		Mungbean genotypes	0.17			28.99**		

TABLE 4.2.5 cont'd.

No. of Expt.	Intercropping	Test factors	Main factors	Interactions	CV(%)	Main factors	Interactions	CV(%)
24	Maize + upland rice	Maize genotypes	15.27**	} 1.16	13.60	0.24	}1.76	22.20
		Leaf cutting of maize	6.94**			0.80		
26	" "	Upland rice genotypes	1.24		19.46	3.86*		19.88
27	" "	Upland rice genotypes	2.44		31.71	3.87*		34.36
28	" "	Upland rice genotypes	3.80*		44.98	21.99**		16.97
30	" "	Management methods	162.41*	} 4.29**	22.74	11.41**	}0.96	16.73
		Upland rice genotypes	2.71			2.34		
37	" "	Row distance of maize	356.79**	} 2.84*	15.61	30.24**	}0.68	24.38
		Leaf cutting of maize	21.84**			3.67*		
38	" "	Row distance of maize	107.90**	} 0.92	30.54	35.61*	}0.29	20.95
		Leaf cutting of maize	5.40**			1.84		
36	" "	Leaf cutting of maize	2.02	} 0.03 } 0.38] 0.51	20.22	3.74	}1.05 }1.20] 0.94	28.74
		Maize genotypes	5.41**	0.72		2.84	1.34	
		Row distance of maize	15.13**			0.21		
34	Maize + sweet potatoes	Maize genotypes	7.01**	} 0.02 } 0.37] 0.30	55.60	3.64	}7.90** }1.53] 1.03	14.58
		Planting system of maize	18.05**	} 1.43		0.27	0.44	
		Row distance of maize	1.85					
35	" "	Maize genotypes	292.40**	} 0.48 }13.09**] 0.92	36.99	4.92*	}1.04 }0.85] 0.23	30.00
		Non sweet potatoes	1.01	} 0.33		0.39	0.44	
		Planting system of maize	14.38**			1.42		
1	Cassava + peanut	Peanut densities	0.43		10.19	18.24**		26.22
33	" "	Nitrogen on peanut	0.28	} 1.21	13.59	0.79	}2.67	19.41
		Nitrogen on cassava	25.44**			16.05**		
5	Cassava + upland rice	Planting date of cassava	13.40**		18.08	29.13**		10.87
41	Sugar-cane + maize				4.80			
		Sugar-cane genotypes	3.87	} 0.31		5.41*	}0.20	10.16
		Maize genotypes	5.19			1.09		
42	" "	Sugar-cane genotypes	5.43**	} 0.01	18.49	33.37**	}0.12	12.72
		Planting distance of maize	0.07			21.84**		
43	" "	Sugar-cane genotypes	65.57	} 22.29**	5.46	0.34	}0.33	2.82
		Between rows distance of sugar cane	0.02			54.88**		
50	" "	Nitrogen on sugar-cane + maize	1.20		8.00	0.62		27.80
51	" "	Nitrogen on sugar-cane + maize	10.97**		4.80	2.18		22.60

TABLE 4.2.5 cont'd.

No. of Expt.	Intercropping	Test factors	Main factors	Interactions	CV(%)	Main factors	Interactions	CV(%)
39	Sugar-cane + onion	Sugar-cane genotypes Within rows distance of onion	1.95 11.10**	} 0.96	6.12	0.46 2.87	} 1.01	36.83
40	Sugar-cane + tomatoes	Sugar-cane genotypes Within rows distance of tomatoes	0.62 2.65	} 0.07	11.35	17.03** 0.97	} 0.17	4.44

} = interaction between two factors

] = interaction between three factors

These two signs will be used later with the same meaning.

TABLE 4.2.6 The result of analysis on comparisons of intercrop versus sole crop yield of the first crop.

	Treatments	Type of intercrop	F-ratio	Mean yield (ton/ha) of the first crop sole	Inter-crop
1	Sole cassava vs intercrop	cassava + peanut	0.52	18.67	18.02
8	Sole maize vs intercrop	maize + mungbean	53.29**	3.33	1.90
9	Sole maize vs intercrop	maize + soybean	2.90	4.12	4.92
16	Planting systems [a)]	maize + peanut	3.04	2.89	1.67
19	Planting systems	maize + peanut	36.39**	2.91	2.54
20	Planting systems	maize + peanut	3.04	2.90	2.73
22	Planting systems	maize + soybean	315.08**	2.18	1.19
23	Planting systems	maize + soybean	284.96**	2.55	1.28
24	Planting systems	maize + rice	131.32**	3.36	1.96
40	Sole sugar-cane vs intercrop	sugar-cane + tomatoes	19.61**	125.00	1.03
42	Sole sugar-cane vs intercrop	sugar-cane + maize	1.80	139.00	121.50
43	Planting systems	sugar-cane + maize	1.51	172.75	161.50
44	Planting systems	sugar-cane + maize	2.50	139.17	127.50
45	Sole sugar-cane vs intercrop	sugar-cane + 2nd crops [b)]	3.82	101.68	96.48
46	Sole sugar-cane vs intercrop	sugar-cane + 2nd crops	9.27**	111.70	99.80
47	Sole sugar-cane vs intercrop	sugar-cane + 2nd crops	20.87**	119.56	102.78
48	Sole sugar-cane vs intercrop	sugar-cane + 2nd crops	2.56	103.76	100.20
49	Sole sugar-cane vs intercrop	sugar-cane + 2nd crops	18.17**	135.62	114.63

a) either sole crop or intercrop

b) look at Section III.2 for details

TABLE 4.2.7 Analyses of variance of the first crop yield equivalence.

No. of Expt.	Intercrop	Test factors	The F-ratio of: Main factors	The F-ratio of: Interactions	CV(%)
7	Maize + peanut	Nitrogen on maize + peanut	12.35**		4.70
16	" "	Peanut densities	5.22*		10.90
17	" "	Planting date of maize + peanut	203.55**		3.70
25	" "	Peanut genotypes	2.13		15.80
6	" "	Nitrogen on maize	2.04	}0.06	8.00
		Population of maize	1.03		
15	" "	Population of maize	32.93**		14.70
18	" "	Planting date of maize	30.23**	}0.08	9.70
		Population of maize	0.79		
19	" "	Maize genotypes	7.35**	}20.07**	4.50
		Population of maize	31.16**		
20	" "	Maize genotypes	23.82**	}0.53	12.90
		Population of maize	15.38**		
9	Maize + soybean	Soybean genotypes	0.57		13.40
29	" "	Soybean genotypes	2.20		27.80
32	" "	Nitrogen on maize	11.28**		7.70
10	" "	Direction of rows planting	0.36	}2.13	3.32
		Within row distance of maize	70.81**		
11	" "	Direction of rows planting	0.20	}3.78*	15.00
		Within row distance of maize	55.88**		
12	" "	Maize genotypes	3.34	}0.53	12.60
		Soybean genotypes	1.62	}0.21	
		Planting distance of maize	0.94		
22	" "	Maize genotypes	15.88**	}1.01	9.90
		Leaf cutting of maize	18.41**		
23	" "	Maize genotypes	4.05	}0.84	10.60
		Leaf cutting of maize	3.18		
31	" "	Maize genotypes	0.04	}0.40	11.70
		Population of maize	1.62		
21	Maize + soybean or upland rice	Types of second crop	5.84*	}1.34	13.80
		Insecticide treatments	1.83		
8	Maize + mungbean	Mungbean genotypes	14.47**		7.30
13	" "	Maize genotypes	2.23	}3.34*	6.70
		Mungbean genotypes	94.99**		
14	" "	Maize genotypes	26.29**	}0.95	12.40
		Mungbean genotypes	17.29**		
24	Maize + upland rice	Maize genotypes	4.30	}0.29	
		Leaf cutting of maize	3.56		8.50
26	" "	Upland rice genotypes	2.56*		14.70
27	" "	Upland rice genotypes	2.10		26.10
28	" "	Upland rice genotypes	16.00**		19.40
30	" "	Management methods	1.14	}3.51**	6.90
		Upland rice genotypes	4.20**		
37	" "	Between row distance of maize	18.48**	}0.36	15.30
		Leaf cutting of maize	1.25		
38	" "	Between row distance of maize	50.56	}0.98	15.80
		Leaf cutting of maize	4.88**		
36	" "	Leaf cutting of maize	3.70	}1.12 }0.80] 0.85	21.90
		Maize genotypes	0.76	}1.48	
		Planted distance of maize	1.11		
34	Maize + sweet potatoes	Maize genotypes	19.20**	}9.03** }1.45] 1.24	12.70
		Planting system of maize	6.12**	}0.31	
		Fertilizer treatments	0.85		

TABLE 4.2.7 cont'd.

No. of Expt.	Intercrop	Test factors	Main factors	Interactions	CV(%)
35	Maize + sweet potatoes	Maize genotypes	1.93	}0.57}4.67**]0.43	23.80
		Nitrogen on sweet potatoes	0.41	}0.28	
		Planting system of maize	0.12		
1	Cassava + peanut	Peanut densities	1.75		8.50
33	" "	Nitrogen on peanut	2.47	}1.03	
		Nitrogen on cassava	8.84**		8.20
5	Cassava + upland rice	Planting date of cassava	25.00**		15.50
2	Cassava + peanut or sweet potato	Intercrop densities	22.67**		10.70
3	Cassava + peanut or soybean or sesame	Type of second crops	59.63**	}1.55	7.80
		Population of second crops	2.59		
4	Cassava + broad bean or sweet potato or upland rice	Type of second crops	1.03	}0.06	8.00
		Population of second crops	2.04		
41	Sugar-cane + maize	Sugar-cane genotypes	2.95	}0.25	4.70
		Maize genotypes	5.42*		
42	" "	Sugar-cane genotypes	4.69	}0.02	17.30
		Planting distance of maize	0.01		
43	" "	Sugar-cane genotypes	64.74**	}21.98*	5.30
		Between row distance of sugar-cane	0.01		
50	" "	Nitrogen on sugar-cane + maize	1.28		7.80
51	" "	Nitrogen on sugar-cane + maize	25.21**		3.30
39	Sugar-cane + onion	Sugar-cane genotypes	0.52	}0.04	6.90
		Within row distance of onion	13.12**		
40	Sugar-cane + tomatoes	Sugar-cane genotypes	1.09	}0.08	9.90
		Within row distance of tomatoes	2.71		
44			0.05		17.90
45			1.25		6.10
46			21.68**		3.60
47			15.53**		3.90
48			0.39		5.50
49			19.45**		5.00

Table 4.2.8 Analysis of variance of the 1st crop yield equivalence of experiment 12.

Source of variation	DF	Mean Square
Block	2	9.6191
Intercropping systems	11	
maize genotypes	1	1.6779
soybean genotypes	5	0.8113
interactions	5	0.2680
Error	22	0.5023
Sole maize Vs intercropping	1	39.6058**
Sole soybean Vs intercropping	1	2.6801

TABLE 4.2.9 Analysis of variance of the 1st crop yield equivalence of experiment 13.

Source of variation	DF	Mean Square
Block	2	0.339
Intercropping systems	11	
maize genotypes	1	2.319
mung bean genotypes	5	98.860**
interaction	5	3.481*
Error	22	1.041

TABLE 4.2.10 The mean and the range of the first crop yield equivalence and the first sole crop yield.

No. of Expt.	Intercropping	The first crop yield equivalence (ton/ha) Intercrop Mean	Range	The first sole crop (ton/ha) Mean	% of means Intercrop/sole crop
6	Maize + peanut	3.37	2.67 - 3.82	2.15	157
7	" "	5.37	4.69 - 6.16	2.08	258
15	" "	3.47	2.11 - 5.22	2.88	120
16	" "	6.12	4.38 - 6.98	2.90	211
17	" "	4.72	3.57 - 6.62	2.70	175
18	" "	4.75	2.15 - 3.63	2.33	204
19	" "	5.50	4.08 - 6.32	2.91	189
20	" "	3.73	2.50 - 6.07	2.90	129
9	Maize + soybean	4.42	3.63 - 6.80	3.09	143
10	" "	2.49	2.30 - 3.17	2.31	108
11	" "	2.39	1.78 - 3.00	2.03	118
12	" "	4.22	2.99 - 5.78	2.13	198
22	" "	1.50	0.77 - 2.09	2.18	69
23	" "	2.34	1.63 - 2.78	2.15	109
21	Maize + soybean or upland rice	4.27	3.56 - 5.57	3.63	118
8	Maize + mungbean	4.11	2.64 - 5.16	3.33	123
13	" "	5.33	2.62 - 7.28	2.90	184
14	" "	4.79	2.17 - 6.91	2.45	196
24	Maize + upland rice	4.20	3.18 - 5.26	3.35	125
1	Cassava + peanut	21.17	15.65 - 26.19	18.67	113
5	Cassava + upland rice	15.46	9.29 - 25.68	12.14	127
2	Cassava + peanut or sweet potatoes	9.75	6.61 - 13.35	7.87	124
3	Cassava + peanut or soybean or sesame	8.63	3.58 - 16.54	5.27	164
4	Cassava + b-bean or s-potatoes or u-rice	13.34	6.33 - 21.26	6.56	203
41	Sugar-cane + maize	73.23	67.01 - 79.04	99.90	73
42	" "	127.50	88.15 - 167.88	138.90	92
43	" "	166.13	92.95 - 210.66	146.91	113
39	Sugar-cane + onion	129.14	113.47 - 151.47	115.01	112
40	Sugar-cane + tomatoes	122.00	97.29 - 148.39	124.94	97

TABLE 4.2.11 Analysis of variance of L_{11} of experiment 12

SOURCE OF VARIATIONS	DF	MEAN SQUARE
Block	2	0.6672
Intercropping systems	11	
maize genotypes	1	0.0117
soybean genotypes	5	0.0218
interaction	5	0.0242
Error	22	0.0464
Sole maize Vs intercrop	1	1.4185**
Sole soybean Vs intercrop	1	3.3102**

TABLE 4.2.12 Analysis of variance of L_{21} of experiment 12

SOURCE OF VARIATIONS	DF	MEAN SQUARE
Block	2	0.6844
Intercropping systems	11	
maize genotypes	1	0.0358
soybean genotypes	5	0.0358
interaction	5	0.0235
Error	22	0.0456
Sole maize Vs intercrop	1	1.6132**
Sole soybean vs intercrop	1	2.8590**

TABLE 4.2.13 Analysis of variance of L_{31} of experiment 12

SOURCE OF VARIATIONS	DF	MEAN SQUARE
Block	2	0.5103
Intercropping systems	11	
maize genotypes	1	0.0555
soybean genotypes	5	0.0246
interaction	5	0.0204
Error	22	0.0378
Sole maize vs intercrop	1	0.9587**
Sole soybean vs intercrop	1	3.3140**

TABLE 4.2.14 Analysis of variance on L_{11} of experiment 13.

SOURCE OF VARIATIONS	DF	MEAN SQUARE
Block	2	0.0129
Intercropping systems	11	
maize genotypes	1	0.1912**
mungbean genotypes	5	0.1694**
interactions	5	0.0352
Error	22	0.0496

TABLE 4.2.15 Analysis of variance on L_{21} of experiment 13.

SOURCE OF VARIATIONS	DF	MEAN SQUARE
Block	2	0.0095
Intercropping systems	11	
maize genotypes	1	0.0632
mungbean genotypes	5	1.8703**
interactions	5	0.0590*
Error	22	0.0182

TABLE 4.2.16 Analysis of variance on L_{31} of experiment 13.

SOURCE OF VARIATIONS	DF	MEAN SQUARE
Block	2	0.0012
Intercropping systems	11	
maize genotypes	1	0.0062
mungbean genotypes	5	0.8490**
interactions	5	0.0381
Error	22	0.0110

TABLE 4.2.17 Analyses of variance of the Land Equivalent Ratio of the average block standardization (i.e. L_{11}, L_{21}, L_{31}).

No. of Expt.	Intercropping	Test factors	L_{11} The F-ratio of Main Factors	L_{11} The F-ratio of Inter-actions	L_{21} The F-ratio of Main Factors	L_{21} The F-ratio of Inter-actions	L_{31} The F-ratio of Main Factors	L_{31} The F-ratio of Inter-actions
7	Maize + peanut	Nitrogen on maize and peanut	1.80		40.90**		32.79**	
17	" "	Planting date of maize and peanut	105.05**		175.67**		190.44**	
6	" "	Nitrogen of maize	4.65	}0.15	6.73*	}0.08	4.79*	}0.07
		Population of maize	1.61		3.83		3.32	
15		Population of maize	2.22		15.47**		8.98**	
18	" "	Planting date of maize	0.54	}0.34	3.35*	}0.29	3.48*	}0.28
		Population of maize	25.54**		56.10**		55.14**	
19	" "	Maize genotypes	24.50**	}4.12	21.63**	}48.41**	24.43**	}39.15**
		Population of maize	35.44**		0.22		0.22	
20	" "	Maize genotypes	0.94	}0.10	12.65**	}0.46	5.97*	}0.41
		Population of maize	2.38		3.92		0.14	
9	Maize + soybean	Soybean genotypes	0.67		0.84		0.65	
10	" "	Direction of rows planting	1.63	}0.56	0.55	}0.56	0.55	}0.56
		Within row distance of maize	0.66		0.66		0.66	
11	" "	Direction of rows planting	22.53**	}0.71	0.93	}0.65	0.74	}0.62
		Within row distance of maize	0.28		0.22		0.22	
12	" "	Maize genotypes	0.25	}0.52	1.86	}0.52	1.47	}0.54
		Soybean genotypes	0.47	}0.06	0.78	}0.08	0.65	}0.04
		Planting distance of maize	0.22		0.25		0.16	
22	" "	Genotypes of maize	12.05**	}1.24	18.38**	}1.16	18.40**	}1.21
		Leaf cutting of maize	0.42		6.03*		3.87*	
23	" "	Genotypes of maize	1.08	}1.03	1.86	}0.81	1.40	}0.81
		Leaf cutting on maize	0.29		1.10		0.72	
24	Maize + upland rice	Genotypes of maize	5.35*	}0.63	3.85	}0.41	2.77	}0.49
		Leaf cutting on maize	3.02		3.38		2.83	
8	Maize + mungbean	Mungbean genotypes	3.57*		13.78**		10.25**	
13	" "	Maize genotypes	9.94**	}1.83	3.47	}3.25*	0.57	}3.45*
		Mungbean genotypes	8.81**		102.94**		76.95	
14	Maize + mungbean	Maize genotypes	11.56**	}0.90	33.79**	}0.82	44.03**	}0.60
		Mungbean genotypes	0.44		13.38**		7.82**	
1	Cassava + peanut	Population of peanut	no valid		no valid		7.41*	
5	Cassava + upland rice	Planting date of cassava	solution		solution		7.86**	

TABLE 4.2.18 Yield and LERs of 2 genotypes of maize intercropped with 6 soybean genotypes of experiment 12.

Treatment	Intercrop Yield (kg/ha) maize	Intercrop Yield (kg/ha) soybean	LER using appropriate individual genotype (L_{11}) L_c	L_s	LER	LER using the average sole treatment (L_{21}) L_c	L_s	LER	LER using the maximum sole treatment (L_{31}) L_c	L_s	LER
A_1B_1	1926	953	0.85	0.55	1.40	0.90	0.62	1.52	0.84	0.49	1.33
B_2	2043	1230	0.89	0.63	1.52	0.96	0.80	1.76	0.89	0.63	1.52
B_3	1992	1004	0.87	0.71	1.58	0.93	0.65	1.59	0.87	0.51	1.38
B_4	1948	805	0.85	0.60	1.45	0.91	0.52	1.44	0.85	0.41	1.26
B_5	2331	945	1.02	0.62	1.64	1.09	0.62	1.71	1.02	0.48	1.50
B_6	2103	1004	0.92	0.53	1.45	0.99	0.65	1.64	0.92	0.51	1.43
A_2B_1	2507	637	1.27	0.36	1.63	1.18	0.41	1.59	1.10	0.32	1.42
B_2	1744	1133	0.88	0.58	1.46	0.82	0.74	1.55	0.76	0.58	1.34
B_3	1891	750	0.95	0.53	1.48	0.89	0.49	1.37	0.83	0.38	1.21
B_4	1976	862	0.99	0.64	1.63	0.93	0.56	1.49	0.86	0.44	1.30
B_5	2235	762	1.13	0.50	1.63	1.05	0.50	1.54	0.98	0.39	1.37
B_6	1771	1063	0.90	0.56	1.46	0.83	0.69	1.52	0.77	0.54	1.32

Sole crop yield (kg/ha)

Maize		Soybean					
A_1	2286	B_1	1739	B_3	1418	B_5	1527
A_2	1979	B_2	1965	B_4	1352	B_6	1891

TABLE 4.2.19 The treatment mean yields of 2 genotypes of maize intercropped with 6 mung bean genotypes of experiment 13.

Intercrop yield (kg/ha)						Sole crop yield (kg/ha)			
Treat-ment	maize	mung bean	Treat-ment	maize	mung bean		maize		mung bean
A_1B_1	2702	1304	A_2B_1	2719	1039	A_1	2810	B_1	1126
B_2	2016	1280	B_2	2870	1102	A_2	2982	B_2	1071
B_3	2730	911	B_3	2632	743			B_3	784
B_4	2282	788	B_4	2723	788			B_4	747
B_5	2387	1016	B_5	2772	787			B_5	797
B_6 a)	2527	23	B_6 b)	2691	19			B_6 a)	30

a) the mung bean genotypes of local Jambe Gede (B_6) was seriously damaged by the schlerotium disease.

TABLE 4.2.20 The mean, the range of L_{21}, L_{31} and the component LER of L_{31}.

No. of Expt.	Intercropping	Test factors	L_{21} LER total Mean	L_{21} LER total Range	L_{31} LER 1st crop Mean	L_{31} LER 1st crop Range	L_{31} LER 2nd crop Mean	L_{31} LER 2nd crop Range	L_{31} LER total Mean	L_{31} LER total Range	% of LER total >1.00	LER total of the best treatment mean
7	Maize + peanut	Nitrogen on maize and peanut	1.33	0.96-1.82	0.39	0.10-0.77	0.72	0.64-0.81	1.11	0.86-1.44	75	1.43
17	" "	Planting date of maize and peanut	1.54	1.19-2.14	0.78	0.58-1.04	0.63	0.41-0.90	1.41	1.08-1.97	100	1.89
6	" "	Nitrogen on maize	1.27	0.96-1.49	0.41	0.16-0.74	0.82	0.59-1.08	1.23	0.94-1.43	94	1.34
		Population of maize										
15	" "	Population of maize	1.61	0.93-2.45	0.48	0.27-0.79	0.78	0.39-1.24	1.26	0.71-1.93	88	1.43
18	" "	Planting date of maize	1.55	1.12-2.17	0.81	0.42-1.34	0.73	0.59-0.95	1.54	1.11-2.15	100	1.87
		Population of maize										
19	" "	Maize genotypes	1.40	1.07-1.67	0.71	0.50-0.98	0.53	0.36-0.77	1.24	0.94-1.45	92	1.43
		Population of maize										
20	" "	Maize genotypes	1.50	1.02-2.37	0.60	0.25-1.05	0.56	0.23-0.79	1.16	0.76-1.77	83	1.44
		Population of maize										
9	Maize + soybean	Soybean genotypes	2.14	1.63-2.83	1.19	0.77-1.84	0.75	0.45-1.35	1.95	1.47-2.63	100	2.08
10	" "	Direction of rows	1.12	0.94-1.42	0.59	0.42-0.75	0.52	0.40-0.79	1.10	0.93-1.40	67	1.18
		Within row distance of maize										
11	" "	Direction of rows	1.12	0.86-1.31	0.46	0.31-0.59	0.58	0.43-0.76	1.04	0.80-1.23	75	1.10
		Within row distance of maize										
12	" "	Maize genotypes	1.56	1.15-2.29	0.89	0.60-1.58	0.47	0.19-0.72	1.34	1.02-2.05	100	1.52
		Soybean genotypes										
		Planting distance of maize										
22	" "	Genotypes of maize	0.83	0.35-1.22	0.45	0.29-0.62	0.28	0.02-0.58	0.73	0.29-1.08	25	1.01
		Leaf cutting on maize										
23	" "	Genotypes on maize	1.34	0.96-1.60	0.41	0.26-0.61	0.84	0.74-1.02	1.25	0.90-1.53	92	1.36
		Leaf cutting on maize										
24	Maize + upland rice	Genotypes of maize	1.29	0.98-1.61	0.50	0.27-0.76	0.71	0.44-0.97	1.20	0.91-1.50	92	1.37
		Leaf cutting on maize										
8	Maize + mungbean	Mungbean genotypes	1.22	0.78-1.53	0.57	0.42-0.72	0.54	0.22-0.78	1.11	0.72-1.38	83	1.27
13	" "	Maize genotypes	1.97	0.83-2.72	0.87	0.72-1.08	0.73	0.08-1.21	1.59	0.80-2.04	83	2.06
		Mungbean genotypes										
14	" "	Maize genotypes	1.72	0.86-2.41	0.99	0.70-1.29	0.42	0.10-0.77	1.41	0.82-1.97	89	1.81
		Mungbean genotypes										
1	Cassava + peanut	Population of peanut	no valid solution		0.97	0.72-1.04	0.33	0.09-0.64	1.29	0.91-1.67	96	1.43
5	Cassava + upland rice	Planting date of cassava			0.90	0.54-1.36	0.55	0.31-0.79	1.44	1.21-1.80	100	1.58

TABLE 4.2.21 Multivariate and bivariate analyses of variance results on the crop yields and the correlations of errors and the angle between the two crops.

No. of Expt.	Intercropping	Test factors	Standard MANOVA The F-ratio of Main Factors	Standard MANOVA The F-ratio of Interactions	Bivariate method The F-ratio of Main Factors	Bivariate method The F-ratio of Interactions	r	Θ
7	Maize + peanut	Nitrogen on maize + peanut	34.80**		20.9706**		0.42	65°
16	" "	Weeding methods	10.81**		5.37**		0.11	84°
17	" "	Planting date of maize + peanut	48.10**		38.57**		0.05	87°
25	" "	Peanut genotypes	1.10		0.99		0.02	89°
6	" "	Nitrogen on maize	39.04**	}1.28	24.56**	}0.92	-0.12	97°
		Population of maize	7.39**		4.65**			
18	" "	Planting date of maize	20.50**	}1.25	14.74**	}0.45	0.19	79°
		Population of maize	44.30**		31.83**			
19	" "	Maize genotypes	18.49**	}43.76**	10.28**	}24.31**	0.41	65°
		Population of maize	52.67**		29.29**			
20	" "	Maize genotypes	55.84**	}0.52	15.70**	}0.34	0.36	69°
		Population of maize	21.32**		27.41**			
9	Maize + soybean	Soybean genotypes	4.45**		2.85**		0.50	60°
29	" "	Soybean genotypes	2.24*		1.98*		0.21	78°
32	" "	Non maize	9.72**		10.01**		-0.46	117°
10	" "	Direction of rows planting	1.33	}2.63*	2.08	}2.61*	-0.45	117°
		Within row distance of maize	2.09		1.84			
11	" "	Direction of rows planting	5.38**	}0.70	3.84*	}0.45	-0.05	87°
		Within row distance of maize	0.89		0.72			
12	" "	Maize genotypes	3.70*	}1.30	2.17	}1.13	-0.19	101°
		Soybean genotypes	3.04**		0.81			
22	" "	Maize genotypes	37.58**	}2.88*	11.07**	}1.30	0.46	63°
		Leaf cutting of corn	54.38**		15.38**			
23	" "	Maize genotypes	8.99**	}2.59	2.34	}1.22	0.53	58°
		Leaf cutting of corn	16.42**		5.47*			
31	" "	Maize genotypes	0.28	}1.45	0.26	}0.98	-0.19	101°
		Population of maize	7.70**		5.51**			
8	Maize + mungbean	Mungbean genotypes	18.92**		17.13**		-0.32	109°
13	" "	Maize genotypes	12.68**	}3.04*	14.71**	}2.10*	-0.36	111°
		Mungbean genotypes	27.58**		20.11			

TABLE 4.2.21 cont'd.

No. of Expt.	Intercropping	Test factors	Main Factors	Interactions	Main Factors	Interactions	r	θ
14	Maize + mungbean	Maize genotypes	29.09**	}0.74	19.32**	}0.59	0.10	84°
		Mungbean genotypes	10.51**		7.65**			
24	Maize + upland rice	Maize genotypes	32.93**	}2.12	4.29*	}1.31	-0.13	97°
		Leaf cutting of maize	6.41**		3.47			
26	" "	Upland rice genotypes	2.45**		3.34**		0.11	84°
27	" "	Upland rice genotypes	3.34**		2.94**		0.16	81°
28	" "	Upland rice genotypes	7.31**		6.72**		0.03	81°
30	" "	Management methods	983.71**	}3.42**	8.65**	}2.53	-0.25	104°
		Upland rice genotypes	3.71**		2.46**			
37	" "	Row distance of maize	101.02**	}1.96*	72.00**	}1.54	-0.04	92°
		Leaf cutting of maize	12.41**		9.07			
38	" "	Row distance of maize	52.04**	}0.77	50.78**	}0.66	-0.32	109°
		Leaf cutting of maize	4.56**		3.99**			
36	" "	Leaf cutting of maize	62.83**	}0.86	13.31**	}0.51	-0.09	95°
		Maize genotypes	5.56**	}1.54 }1.11]1.03	4.12*	}1.06 }0.84]0.74		
		Row distance of maize	9.73**		6.24**			
34	Maize + sweet potatoes	Maize genotypes	929.99**	}6.85**	12.00**	}3.98*	-0.31	108°
		Planting systems	17.69**	}1.28 }1.35]1.13	19.09**	}2.62* }5.41**]1.81		
		Row distance of maize	1.86		1.92			
35	" "	Maize genotypes	791.64**	}1.08	12.36**	}0.80	-0.10	96°
		Non sweet-potatoes	1.09	}0.53 }6.69**]0.87	0.70	}7.23** }8.54**]1.20		
		Planting system of maize	9.63**		6.89**			
1	Cassava + peanut	Peanut densities	7.83**		6.14**		-0.27	106°
33	" "	Non peanut	9.10**	}2.60*	1.50	}1.89	-0.18	100°
		Non cassava	15.09**		11.37**			
5	Cassava + upland rice	Planting date of cassava	12.80**		6.60**		-0.19	101°
41	Sugar-cane + maize	Sugar-cane genotypes	6.46**	}0.19	3.02	}0.19	0.16	81°
		Maize genotypes	3.59*		2.75			
42	" "	Sugar-cane genotypes	16.85**	}0.14	19.15**	}0.07	-0.50	120°
		Planting distance of maize	11.57**		8.80**			
43	" "	Sugar-cane genotypes	27.49**	}3.74*	15.85**	}7.21**	0.34	70°
		Between row distance of sugar-cane	23.74**		14.38**			
50	" "	Non sugar-cane + maize	1.21		0.81		0.05	87°
51	" "	Non sugar-cane + maize	12.20**		5.39**		-0.65	130°
39	Sugar-cane + onion	Sugar-cane genotypes	1.69	}1.40	0.98	}0.80	0.04	88°
		Within row distance of onion	7.58**		4.91*			
40	Sugar-cane + tomatoes	Sugar-cane genotypes	9.58**	}0.13	7.48**	}0.18	0.42	65°
		Within row distance of tomatoes	1.86		2.34			

TABLE 4.2.24 The availability of sole crops and their function in each intercropping experiment.

No. of Expt.	The availability of sole crops	The function of sole crops in the experiment
1	complete	as a control
2	} complete, but	as treatments
3	} involved more	" "
4	}. than two crops	" "
5	complete	as a control
6	"	as a control
7	"	as treatments
8	"	" "
9	"	" "
10	"	as a control
11	"	" " "
12	"	" " "
13	"	" " "
14	"	" " "
15	"	" " "
16	"	as treatments
17	"	" "
18	"	as a control
19	"	as treatments
20	"	" "
21	"	" "
22	"	" "
23	"	" "
24	"	" "
25	No sole crops	——
26	" " "	——
27	" " "	——
28	" " "	——
29	" " "	——
30	" " "	——
31	" " "	——
32	" " "	——
33	" " "	——
34	" " "	——
35	" " "	——
36	" " "	——

37	" " "	——
38	" " "	——
39	Only the 1st crop	As a control of
40	" " " "	the 1st crop
41	" " " "	" " "
42	" " " "	" " "
43	" " " "	" " "
44	" " " "	" " "
45	" " " "	" " "
46	" " " "	" " "
47	} only the 1st crop,	As a control of
48	} also involved more	the 1st crop
49	} than two crops	" " "
50	no sole crops	" " "
51	" " " "	" " "

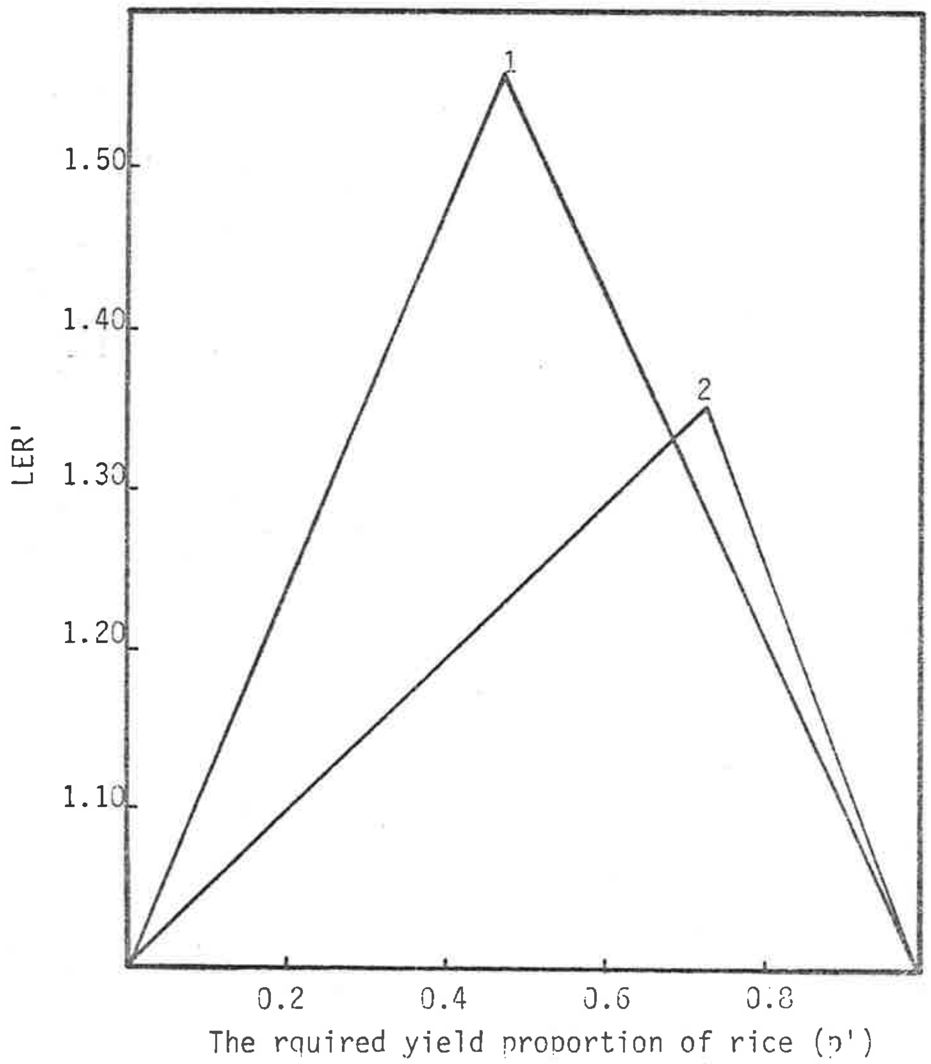


Fig.4.2.1 The new effective LER curves for two intercropping treatments of experiment 5 (1 and 2 are 20 and 40 days of planting of cassava after sowing of the upland rice).

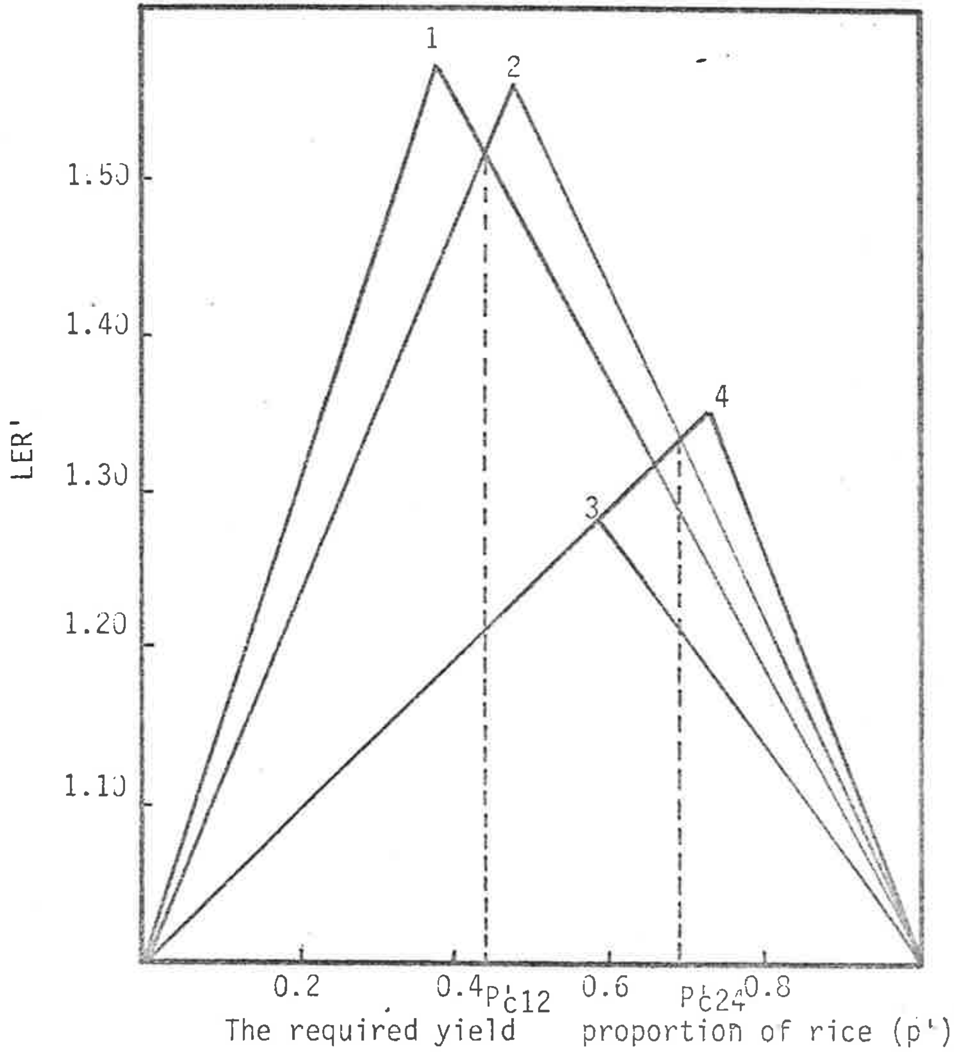


Fig.4.2.2 The new effective LER curves for intercropping treatments of experiment 5. 1,2,3 and 4 represent 0,20,40 and 60 days of planting of cassava after sowing of the upland rice.

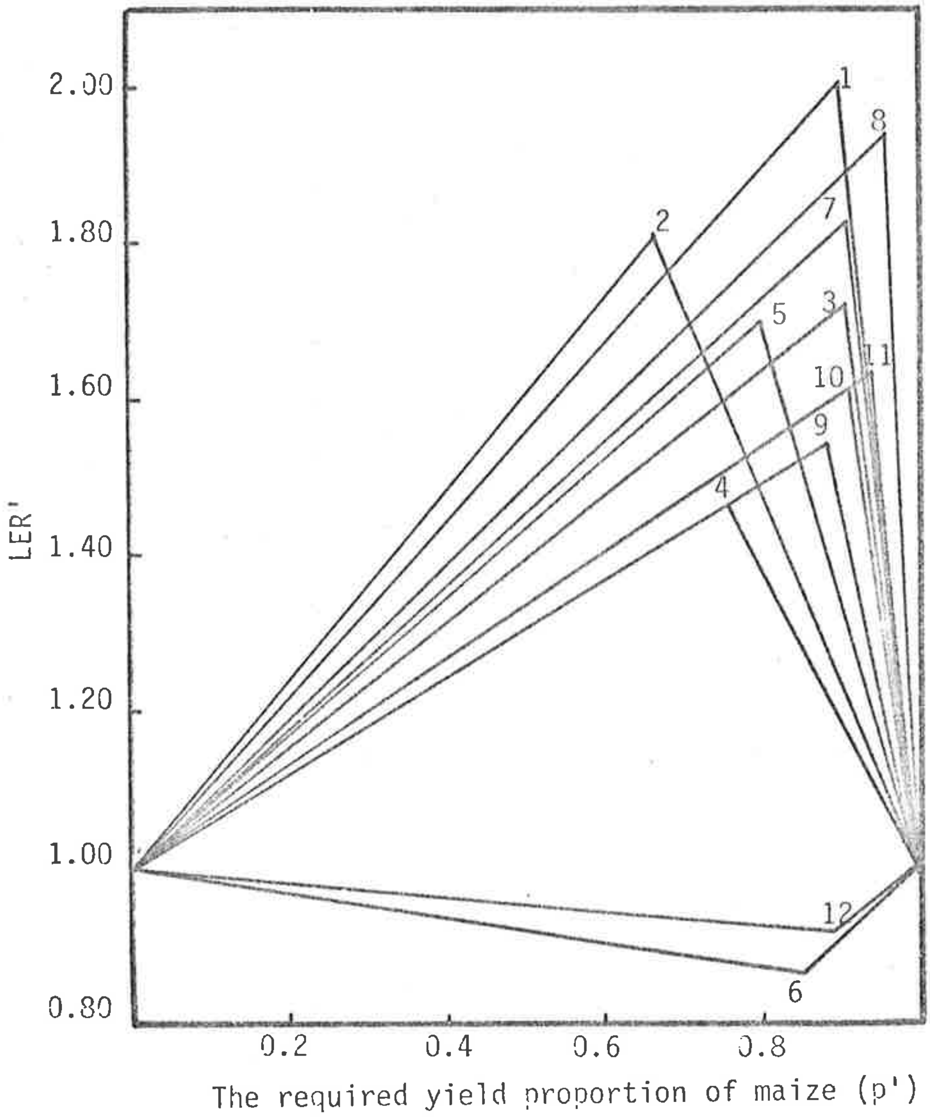


Fig. 4.2.3 The new effective LER curves for intercropping treatments of experiment 13.
1 = A_1B_1 2 = A_1B_2 3 = A_1B_3 4 = A_1B_4 5 = A_1B_5 6 = A_1B_6
7 = A_2B_1 8 = A_2B_2 9 = A_2B_3 10 = A_2B_4 11 = A_2B_5 12 = A_2B_6

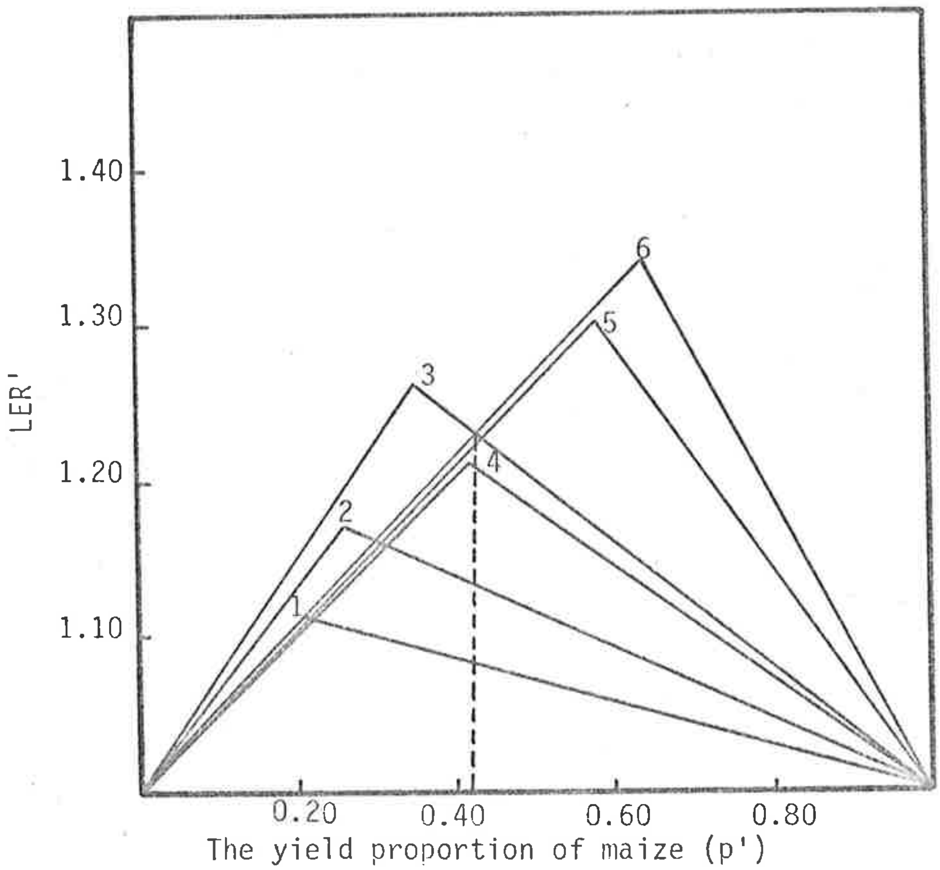


Fig.4.2.4. The new effective LER curves for intercropping treatments of experiment 6. $1=A_1B_1$; $2=A_1B_2$; $3=A_1B_3$; $4=A_2B_1$; $5=A_2B_2$; $6=A_2B_3$.

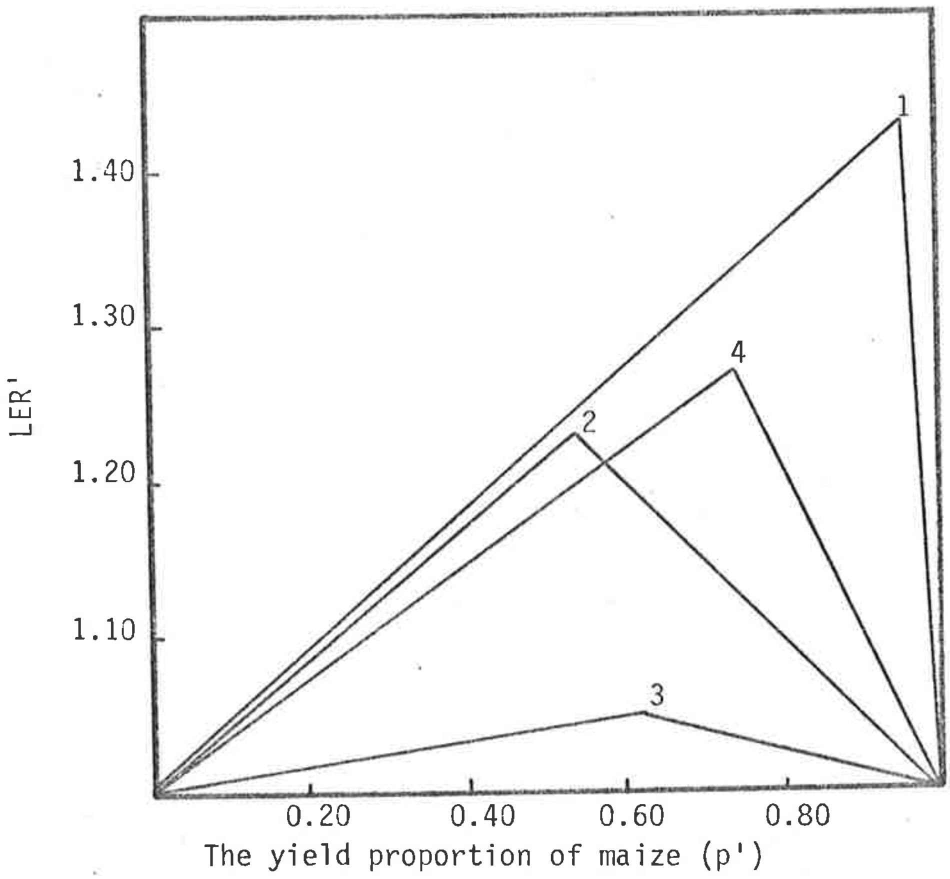


Fig.4.2.5. The new effective LER curves for intercropping treatments of experiment 19. $1=A_1B_1$; $2=A_1B_2$; $3=A_2B_1$; $4=A_2B_2$.

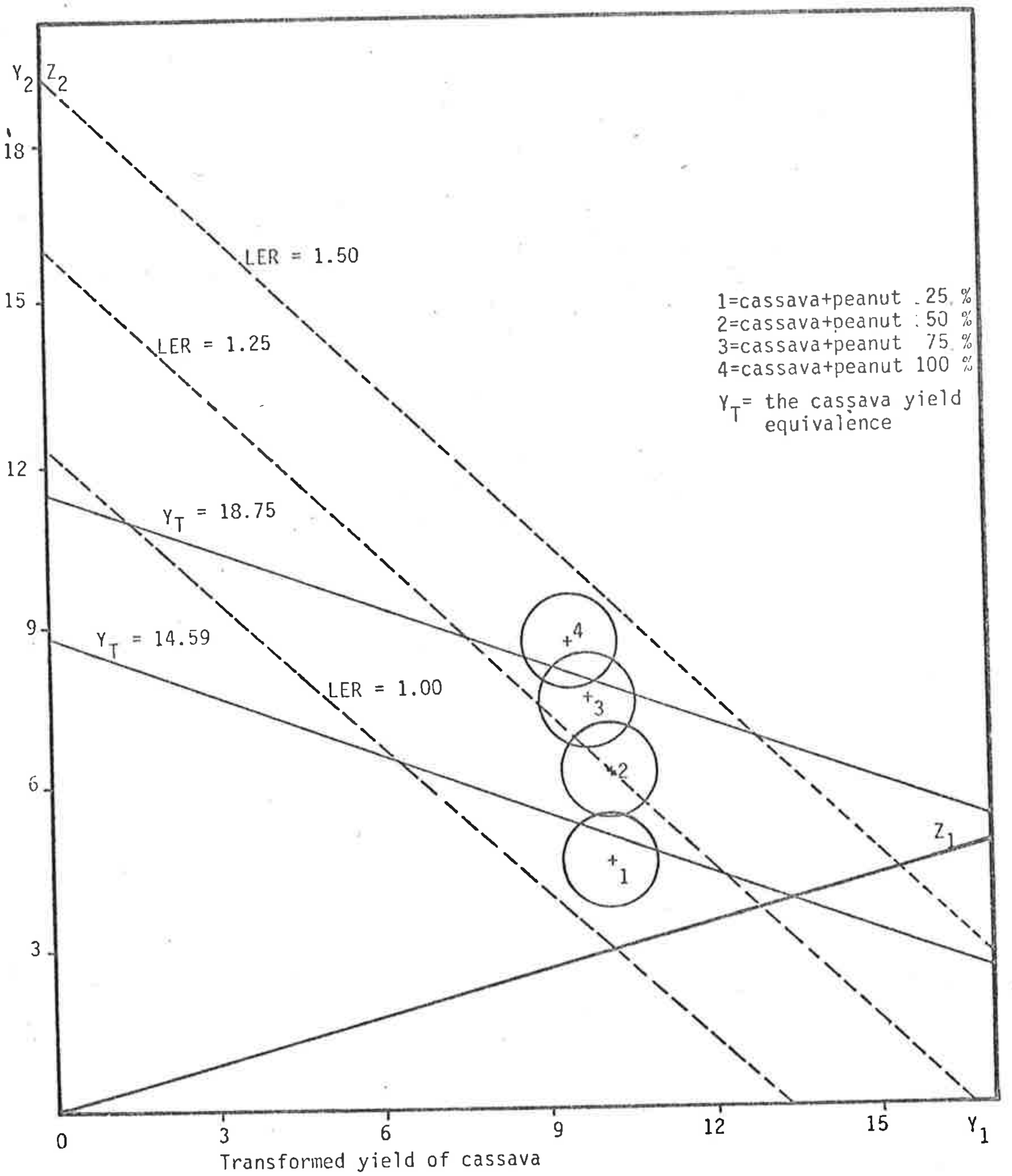


Fig. 4.2.6 Results of data of experiment 1 to show the effect of population densities of peanut. The solid lines show contours of equal cassava yield equivalence (i.e. 18.75 and 14.59 ton/ha). The pecked lines show contours of equal Land Equivalence Ratio.

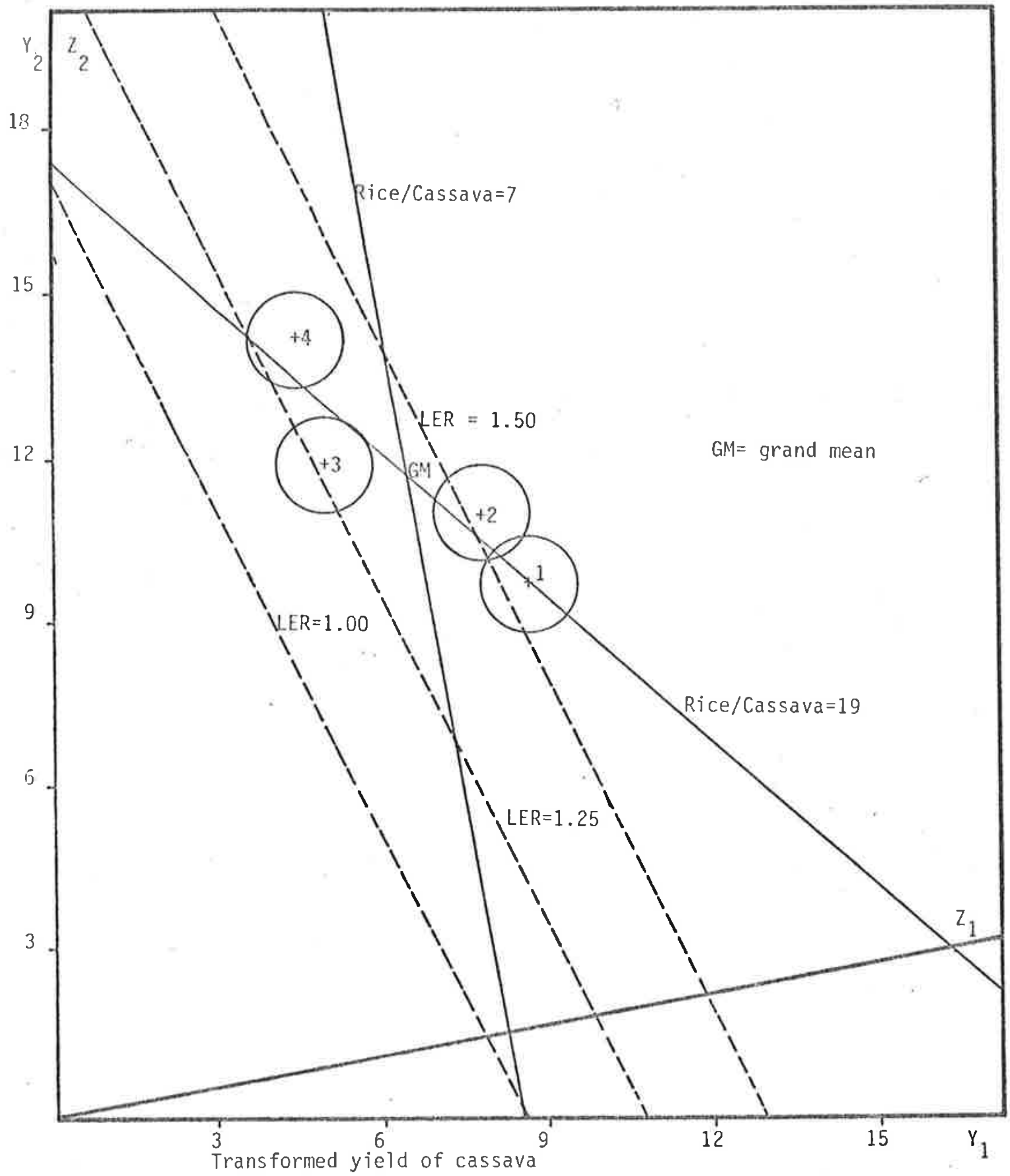


Fig. 4.2.7 Results of data of experiment 5 to show the effect of date of planting of cassava. The solid lines show the contours of cassava yield equivalence at different ratios of price of rice/cassava. The pecked lines show contours of equal Land Equivalent Ratio. 1,2,3 and 4 represent 0,20,40 and 60 days of planting of cassava after sowing upland rice.

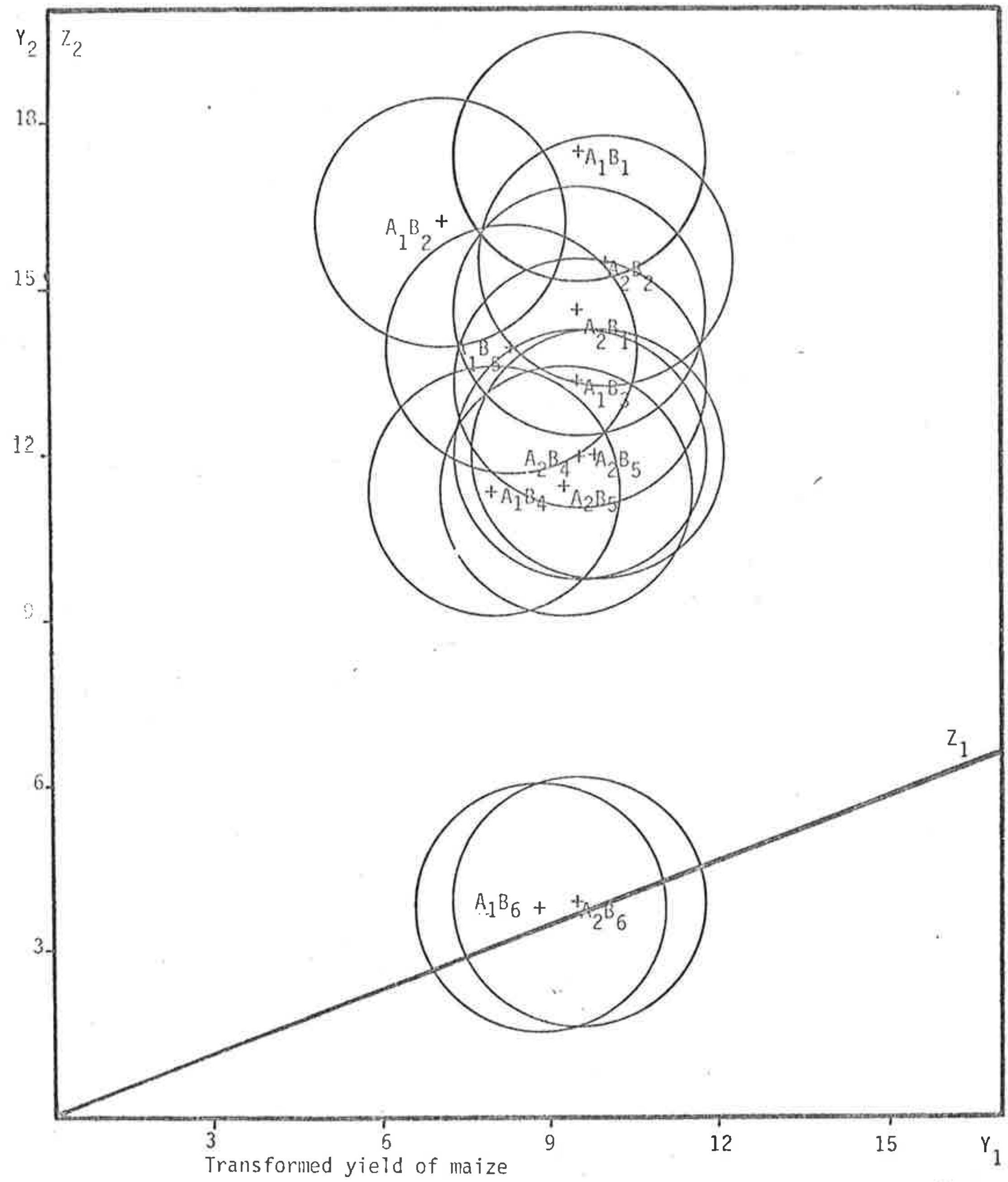


Fig. 4.2.8 Results of data of experiment 13 to show the effects of maize and mungbean genotype combinations. A_i and B_j are the maize and mungbean genotypes.

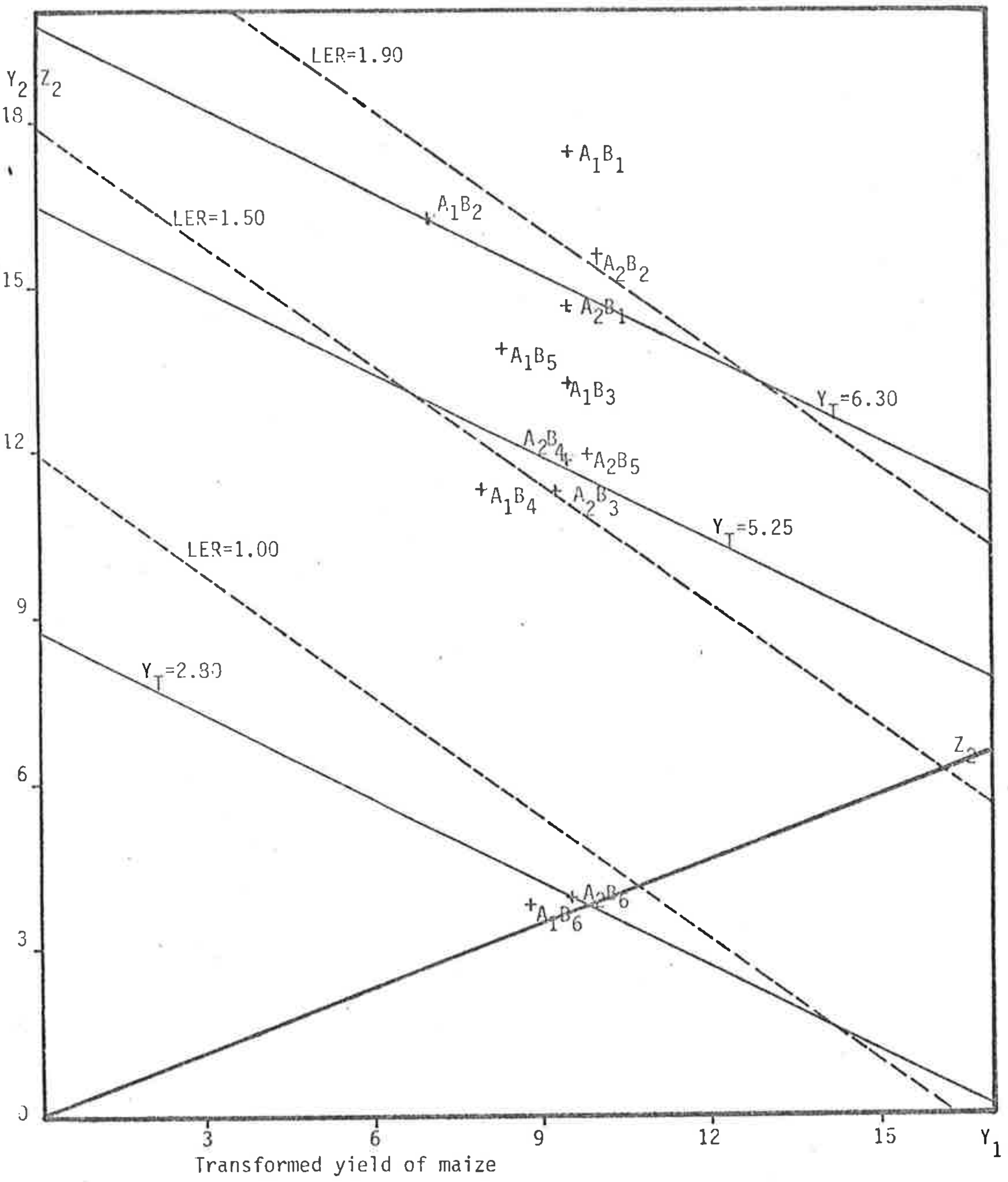


Fig. 4.2.9 The straight lines represent equivalence of maize yield at harvest time (i.e. solid lines) and the Land Equivalent Ratio (i.e. pecked lines) of experiment 13. A_i and B_j are the maize genotypes and mungbean genotypes respectively.

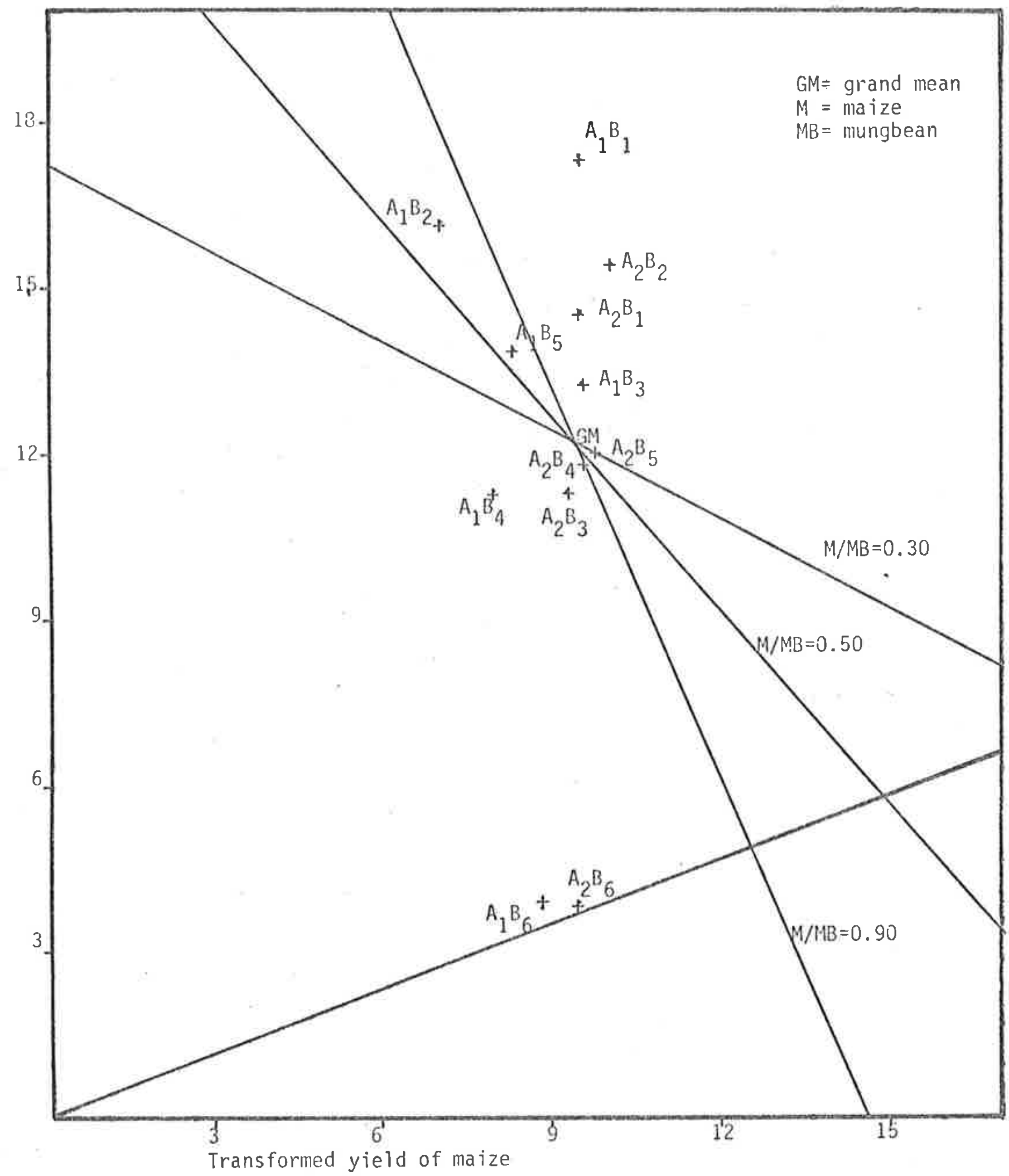


Fig. 4.2.10 The straight lines represent the equivalence of maize yield of experiment 13 at different ratios of the price of maize/mungbean (i.e. 0.30, 0.50 and 0.90). The ratio of the price at harvest time was 0.30.

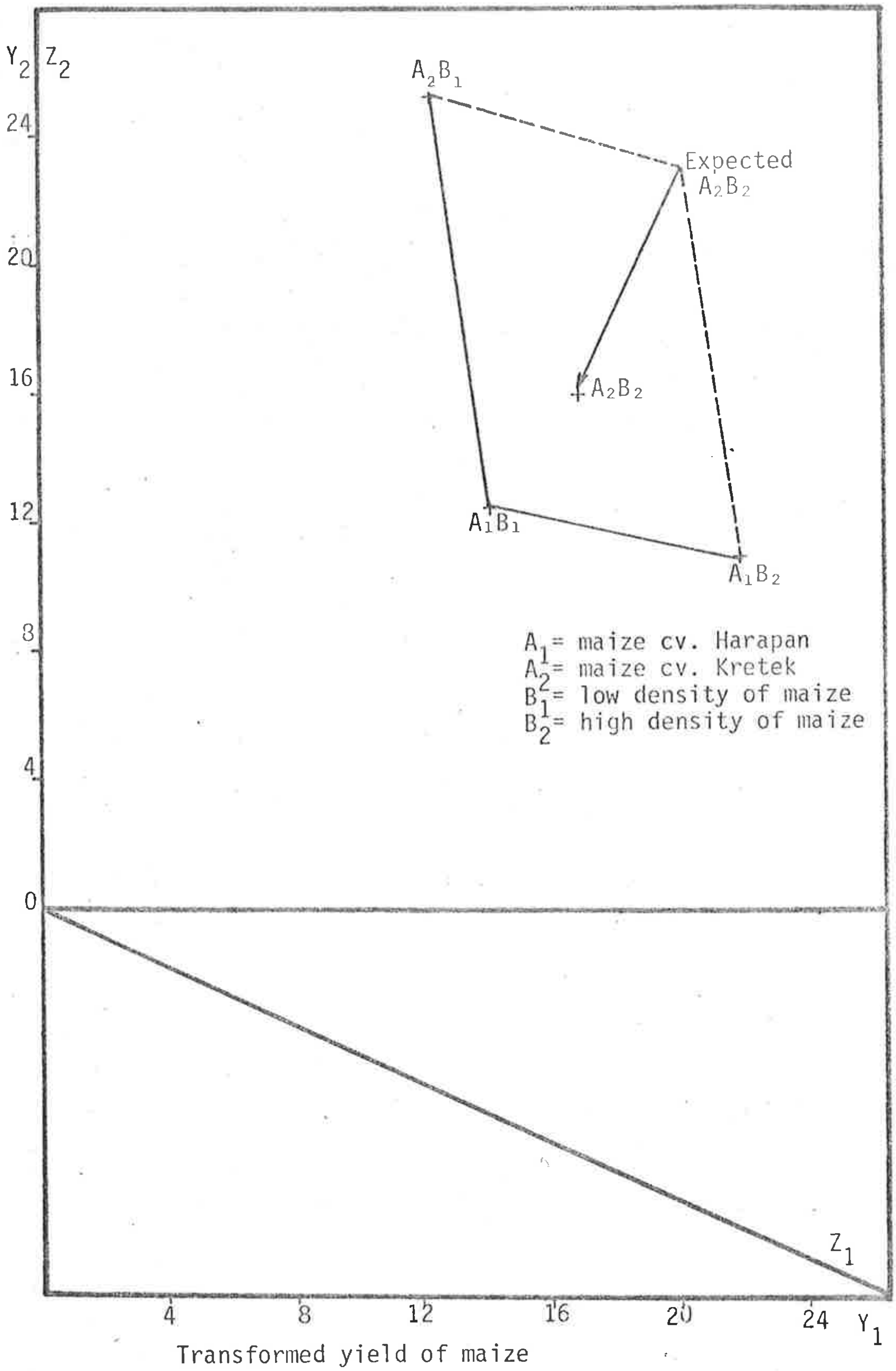


Fig.4.2.11 The interaction between maize genotypes and maize population in the bivariate axes of experiment 19.

IV.3. CONCLUSIONS

The distribution of the ratio of two non-negative normally distributed variables can take many different forms. This is one of the reasons why many statisticians doubt the usefulness of the Land Equivalent Ratio concept in interpreting the results of intercropping data. The study showed (Section IV.1) that using the parametric models in intercropping systems, the distribution of the residuals of the six standardization methods for calculating the LER was quite close to normal, as long as there were no outliers in the data. The variance of residuals after fitting of row and column effects was also quite homogeneous. Furthermore, most of the coefficients of variation obtained after using the six methods were also quite small. In fact, the coefficient of variation of the six LERs was in each case smaller than the coefficient of variation for each crop yield analysed separately. This could be explained by compensation between crops.

Although the choice of standardization (average block vs. each block, or each sole treatment vs. average sole treatment, or maximum sole treatment) is difficult to summarize, I conclude that one should use either L_{21} or L_{31} (i.e. the average sole treatment or the maximum sole treatment of average block standardization) for easy calculation and reliability of comparison between the intercrop treatments (Section IV.2). The calculation of LER using the appropriate sole treatment is useful in comparing intercrop treatments against the appropriate sole crop, but not for comparing between intercrop treatments. The study also found that there was a tendency to exclude the sole crop from the intercropping experiments so the calculation of LER is simply dividing the intercrop yield by the maximum or the average yield of sole crops from that site. When knowledge of sole crop yield is desired then growing sole crop outside of the experiment plots with a larger plot size is possible.

The assumption of the equality of correlation between the two crops for all treatments in the intercropping experiments that involved genotype comparisons is satisfied in general. However, for the experiments that involved densities or fertilizer comparisons, the association varied from mutual cooperation to competition. Therefore, it is necessary to realize that in some types of experiments, the hypotheses of the equality of correlation for all treatments need to be tested, as well as those of the hypotheses of treatment means.

As I noted earlier, if there is more than one characteristic of interest, determining the best treatments if difficult without knowing the criterion of the "best". The study showed that keeping a full yield of the main crop is not a simple matter, therefore analysing each crop yield separately will not solve the problem completely. The combined analysis should in some way be done, preferably by the LER and its extension, the new effective LER. The argument for LER as against monetary value is that the monetary analyses will change with the market. The study has shown that the maximum first crop yield equivalence at harvest time could be the lowest one in another season or year. The price fluctuations of two crops will be rendered much worse by everyone producing the same crop at the same time while simultaneously requiring the other crop also.

The highest LER sometimes does not mean anything to the farmer as his requirement of staple food is not fulfilled from that system. A plot of the results on bivariate axes clearly displays the magnitude of the crop yields or the component LERs. From Section IV.2, in interpreting the LER values we should not only consider the LER total, but also the component LER of each crop as the two crops provide different requirements to the farmer. Though the assumptions underlying the bivariate method in a certain experiment may not be satisfied, the graphical display meets the dual need, that is, the significance of the test (i.e. if the assumptions are satisfied) and the magnitude of two crop yield or component LER of those two crops as responses to treatments. The study also showed that in some cases the highest LER does not always come from the highest yield of the main crop as well. Again, I emphasize that we should not only work on the combined yield analyses through the LER total, but also take into account the main crop that is required by the farmer.

The study offers an alternative criterion of the best treatment and develops the model by means of the new effective LER. The best treatment is defined as that which has the yield of the main crop meeting the farmer's requirements and which also has the highest biological efficiency in terms of the new effective LER. By having the general criterion of the yield proportion of the main crop required by the farmer, we could work on the new effective LER. As shown in Section IV.2.4.1, the model is simple, and the results are more appropriate in the field situation. We must use a range of methods to analyse intercropping data. The results might be different, but the important factor is how should we support or to explain our previous results more completely by performing other analyses. Again, I believe that by using the LER with the magnitude of component LER as in the bivariate analysis and the new effective LER together will be useful in interpreting intercropping data.

V. THE CROPPING SYSTEMS × ENVIRONMENT INTERACTION AND YIELD STABILITY OF INTERCROPPING SYSTEMS

1. INTRODUCTION

It is desirable that the results of research be appropriate to avoid a range of locations and have been carried out over several seasons (Cochran and Cox, 1957). It has been widely shown that the effectiveness of plant nutrients for different genotypes of a crop usually vary across the locations and seasons so it is difficult for the result of an experiment in a certain location and season to be applied to other locations and seasons; that is, ones needs of interactions between genotypes or cropping systems and environment. As a result, successful new genotypes or cropping systems must show high performance for yield and other essential agronomic traits over a wide range of environmental conditions (Finlay and Wilkinson, 1963; Singh, 1975; Jodha, 1979 and Becker, 1981).

Intercropping systems give the important advantages to a small farmer such as diversity of diet, income resources and increases of yield stability (Jodha, 1979; Quarshie, 1979; Rao and Willey, 1980; Gomez and Gomez, 1983).

The mechanism of yield stability is suggested to be some kind of biologic compensation, that is, one condition is favourable for one crop, and unfavourable for the other, or vice versa so that the crops to some extent may compensate each other (Jodha, 1979; Francis, 1980; Rao and Willey, 1980). The other mechanism suggested is buffering against pests and diseases (Trenbath, 1974 and Fisher, 1977). From the economic point of view, Francis (1980) emphasized that as prices fluctuate the two crops in the intercrop buffer fluctuations in total income.

Although its importance was highlighted 35 years ago by Aiyer (1949), there is still very limited work on cropping systems and environment, studies which are also often referred to as stability analyses in intercropping systems (Rao and Willey, 1980).

The previous work on stability analysis of mixed crops has mainly been directed to mixtures of same crop with different genotypes (Allard, 1961; Rasmuson, 1968; Marshal and Brown, 1973; Trenbath, 1974; Quarshie, 1979 and others). The general conclusion from these works is that mixtures on the average are more stable than their sole crops, and sometimes more so than their most stable sole crop. The other interesting results was that complex mixtures are more stable than simple mixtures (Rasmuson, 1968). Hence, greater improvements in the mixture might be expected where there are big differences between component crops in the mixtures such as in the intercrop situation (Rao and Willey, 1980).

Fisher (1976, 1977) showed that yield compensation occurred on maize and bean intercrops which suffered damage due to pest or disease. The compensation, however, does not exist when the limiting growth factor for a system is water. In sorghum and pigeonpea or castor or groundnut intercropping systems, the crop combinations gave yield advantages over a wide range of environmental conditions (Rao et al., 1979; Francis, 1980), though the advantages were not greater under stress (Rao and Willey, 1980). From these results, explanations for stability in intercropping systems are still inconsistent with some of the evidence. Harwood and Price (1976), for example, also observed that the compensation effect on intercropping was only marginal.

The other idea of conducting the same experiment over different locations and seasons in intercropping systems was aimed to study cropping systems or cropping combinations and environment interaction (Singh, 1975; Francis et al, 1978a, 1978b; Francis, 1980 and Gomez and Gomez, 1983). The experiments were carried out on the assumption that the best genotypes as sole crops will also be optimal in the intercrop situation. Like the study of stability, these experiments have been inconsistent and inconclusive (Francis, 1980).

While the past work of stability analyses was mainly concentrated on comparing the stability between sole crop and intercrops, the present study is designed not only to compare those two systems but also to compare the stability between intercropping treatments. The study is also designed to evaluate cropping systems or cropping combinations and environment interaction over a range of intercropping experiments.

2. THE EXPERIMENTS AND STATISTICAL METHODS

1. The experiments

It has been mentioned earlier that the stability analyses of genotypes or cropping systems and environmental interaction in intercropping experiments are still few in number. Part of the problem is that only limited data are available. The experiments that have been conducted are still at the stage of trying to get the best combination of two crops or the best management practices in a certain cropping combination and even so the results are still inconclusive. As can be seen in Section III.2, the main data are from one research institute, i.e. the Research Institute of Food Crops at Bogor and its branches at Malang and Sukamandi. While the results should be consistent, this does not seem to be entirely the case. The genotypes or cropping systems and environment interaction is not so recognised as repetitions of the same experiments are limited both in locations and seasons or years. Hence, as in studies such as that of Rao and Willey (1980), in this study the stability of sole crop versus intercrop will be assessed by using different experiments but the same type of crop combination. The repetition of the same experiments over locations or seasons was available for experiments without sole crop treatments. Therefore it is possible to assess the stability of yield between intercrop treatments more precisely. The technical report data from the Research Institute of Food Crops at Bogor and Malang (Anonymous, 1977, 1980a, 1980b; Ismail et al., 1978 and Basa et al., 1980) will also be used together with data that have been described in Section III.2. The reason for using those published data, is that some of them were the repetition of some experiments in Section III.2, but the raw data were no longer available.

2. Statistical Methods

Plant breeders and agronomists generally agree on the importance of phenotypic stability, but they are still arguing on the most appropriate definition of stability and on a statistical measure of stability in yield trials and even more in trials of intercropping systems (Rao and Willey, 1980 and Becker, 1981). Eberhart and Russell (1966) and Becker (1981) distinguished two concepts of phenotypic stability, i.e. (i) a stable genotype should have a minimal variance under a wide range of environmental conditions ('biological concept'), and (ii) a stable genotype should always show the yield expected at the level of productivity of respective environment, i.e. a genotype which shows no genotype × environment interaction ('agronomic concept'). Unless we know what is meant by the stability of yield choosing the appropriate statistical method will be difficult. As sometimes happens, different statistical methods of measuring yield stability give different conclusions. In this study, therefore, the definition of stable cropping systems or cropping combinations will be that implied by the agronomic concept.

The statistical methods for measuring yield stability and the study of environments and cropping systems interaction will be adapted from sole crop and intercropping systems (Hill, 1975; Francis and Sanders, 1978; Francis, 1980; Rao and Willey, 1980; Gomez and Gomez, 1983). The methods are the correlation technique, the combined bivariate analysis of variance, the coefficient of variation, the regression technique and assessing the risk of falling below a given disaster level of the first crop yield equivalence (e.g. maize yield) and the relative yield.

A simple linear correlation coefficient between the performance of genotype or cropping systems in any two environments provides a measure of the magnitude of the interaction between genotype or cropping system and environment (Francis et al. 1978a, 1978b; Francis, 1980, Gomez and

Gomez, 1983). A small interaction between genotype or cropping system and environment is indicated by a value of r close to +1. On the other hand, on r values of zero or close to zero indicates inconsistency of yield across the environments. A value of r close to -1 indicates a very large interaction.

The combined bivariate analysis of variance due to Pearce and Gilliver (1978, 1979) and Gilliver and Pearce (1983) is set out in Section II.1. The necessary assumption for carrying out significance tests on the combined results of two or more experiments is that the variance-covariance matrices of the errors should be homogeneous.

The details of the method for testing the homogeneity of covariance matrices are given by Morrison (1976), but can be simplifed for two variables or two crops as in this study. The test is a generalization of Bartlett's test for the homogeneity of k variances, and in it the determinants of the sample covariance matrices assume the role of generalized variances. Suppose we have k separate experiments with error SSP_s, E_1, E_2, ..., E_k each on e degrees of freedom. The pooled error SSP can be calculated as

$$A = \frac{1}{k} \sum_{i=1}^{k} E_i$$

The test statistic to assess the variation of the error SSP_s is

$$Me^{-1} \sim \chi^2_{3(k-1)} \qquad (5.1)$$

where

$$M = e(k \ln|E| = \sum_{i=1}^{k} \ln|E_i|)$$

$$e^{-1} = 1 - 0.72 \frac{k+1}{k.e}$$

The regression technique of Yates and Cochran (1938) and Finlay and Wilkinson (1963) will be used, which involves regression of yield of each genotype or cropping system, in several environments, on an index of the environmental mean yield.

The basic model used in this study is the same as in genotype-environment analyses; that is,

$$y_{ijk} = \mu + g_i + e_j + I_{ij} + E_{ijk} \qquad (5.2)$$

where

y_{ijk} = the kth replicate value at the jth site for the ith genotype

μ = overall mean yield

g_i = effect of ith genotype

e_j = effect of jth environment

I_{ij} = interaction between ith genotype and jth environment

E_{ijk} = effect of plot

The model is developed on the basis that the I_{ij} have mean zero and variance V_I.

The improvement of Yates and Cochran (1938) and Finlay and Wilkinson (1963) was to consider how I_{ij} might depend upon e_{ij}; in other words, beginning with the linear model, to examine the regression of I_{ij} on e_j, by computing β_i for each of the m genotypes, using the model,

$$y_{ij} = \mu + g_i + (1 + \beta_i)e_j + d_{ij} \qquad (5.3)$$

where

$$\beta_i = \sum_j I_{ijej} / \sum_j e_j^2$$

and

$$d_{ij} = \text{departure from the model.}$$

The two important stability parameters in this type of analysis are the coefficient of regression and the genotypic mean yield over all environments. A regression coefficient close to 1.0 which is associated with high mean yield describes genotypes with general adaptability; when associated with low mean yield, genotypes are poorly adapted to all environments. Regression values above 1.0 indicate genotypes with increasing sensitivity to environmental change (below average stability) and greater specificity of adaptability to high-yielding environments. On the other hand, the regression coefficients below 1.0 describe greater resistance to environmental change (above average stability), and therefore increasing specificity of adaptability to low yielding environments.

Rao and Willey (1980) argued that in adapting such regression techniques for intercropping systems there can be problems in deciding which cropping system should be used to calculate the environmental mean. Freeman and Perkins (1971), however, emphasized that there are several ways to obtain a measure of the combined effect of all relevant factors operating in an environment. One of them is to use one or more genotypes or cropping systems as a group that can be regarded as a standard for assessing the environment effect. In this study, six different methods of calculating the environmental mean yield will be assessed, namely:

(i) the mean yield of the first sole crop

(ii) the mean yield of the second sole crop

(iii) the mean of the first crop in sole crop and intercrop yield

(iv) the mean of the second crop in sole crop and intercrop yield

(v) the mean of (iii) and (iv)

(vi) as in (v) but in terms of the relative yield.

The relative yield was calculated by using the overall mean yield of the appropriate sole crops with the same crop combination.

The other method for assessing the stability of yield is that of using the risk of obtaining below a given disaster level of maize yield equivalence and the relative yield. The method can be summarized as follows: if Y is the maize yield equivalence or the relative yield and $\bar{Y}$ and S_Y^2 are the mean and variance of Y respectively, then

$$Z = \frac{Y_D - \bar{Y}}{S_Y} \qquad (5.4)$$

where

Y_D = a given disaster level of maize yield equivalence or relative yield.

By assuming that Z is a standard normal variate, then from a table of the normal distribution we obtain $P(Y \leqslant Y_D)$.

3. RESULTS

It is important to accept or to reject the hypothesis that the best cultivars selected in sole crops will also be useful in intercrop situations, and to design and implement a selection program which takes into account the magnitude of the genotype and cropping system interaction in each crop. Data for different types of intercrops are summarized in Table 5.1. The simple correlations were calculated for yields and ranks between sole crop and intercrop. The correlations between yield ranks across the two systems were similar to the correlation for actual yields as one would expect. They were not always consistent for the same crop in different intercrops and even between crops themselves. For example, the correlations of maize in general were significantly greater than zero when it was intercropped either with peanut or soybean, but not significant in association with mungbean. Mungbean also gave correlations significantly greater than zero between sole crop and intercrop. However, the correlations of soybean, peanut and sugarcane across the two systems in general were not significant and some were negative though not significantly so. These results confirm interaction between genotypes and cropping system interaction and complicate the breeding programme. The best genotype selected under sole crop will not necessarily be best in intercrop as well. The lack of consistency in performance of those genotype and cropping systems is stronger over different environments.

To examine the consistency of sole crops and intercrops across different environments, the correlations for yield and ranks were also calculated across the two repeated experiments. The results of this test can be seen in Table 5.2. From this table, it appears that only a few of them are significantly positively correlated across the two environments. Again the values of rank correlations were similar to the yield correlations. The low or negative values of these correlation coefficients confirm the strong environmental influence on yields of the crops. These results indicate the presence of cropping systems and environmental interaction. The interactions tend to occur in the intercrop situation as was shown by the low or negative correlations. These results are not surprising since the situation in intercrops is more complex than in sole crops. The environmental factors that are involved in intercrops arise not only from the different locations or seasons but also from the other crop.

As the experimenter's interest lies in comparing between intercrop treatments rather than between sole crops and intercrops, we examine in more detail the intercrop environment interaction. This interaction effect can also be examined by the combined bivariate analysis of variance. The necessary assumption in combining experiments in the bivariate analysis, is that the variance-covariance matrices should be homogeneous between experiments. The results of the tests on variance-covariance matrices appear in Table 5.3. Except between experiments 37 and 38 and 50 and 51 the variance-covariance matrices are homogeneous. Therefore, for the other repeated experiments, it is possible to combine results to get better precision.

By partitioning the intercrop treatments we can examine the interaction of the environment and treatment effects in more detail. This was done for the combination of experiments 13 and 14 and the combination of experiments 26, 27 and 28.

The first combined experiments were intercrops between maize and mungbean in different seasons (i.e. rainy season and dry season). The result of the combined bivariate analysis of experiment 13 and 14 is presented in Table 5.4. The analysis shows, in spite of the significant effects of seasons, maize genotypes and mungbean genotypes, there are strong interactions between maize genotypes and season effects. This results agrees with Table 5.2 where the correlation of maize intercrop across the environments of experiments 13 and 14 was negative which indicates a fluctuation of seasonal effect.

Table 5.5 presents the bivariate analysis of the combination of experiments 26, 27 and 28. These experiments were intercrops of maize and different upland rice genotypes in three locations (Tulang Bawang, Baturaja and Way Abung). Again, there is a strong interaction between upland rice genotypes and location effects. The other results of the combined bivariate analyses are presented in Table 5.6 (combination of experiments 10 and 11) and Table 5.7 (combination of experiment 22 and 23). From these two tables it also appears that the interaction between environments and intercrop treatments cannot be ignored.

As a major goal of the bivariate analysis lies in the graphical interpretation, the results of this analysis are also presented in Figures 5.1 to 5.4. In Fig. 5.1a the joint effects of maize genotypes and seasons can be seen for experiments 13 and 14. The four mean points, in fact, do not form a rectangle, which means that there are strong interactions between maize genotypes and seasons (Gilliver and Pearce, 1983). The interaction effect can also be determined from the yield of maize in different seasons in the figure. In the rainy season, the yield of maize cv. Harapan was lower than cv. Kretek, but higher in the dry season. In Fig. 5.1b, the effects of mungbean genotypes over two seasons can be examined. The mean points clearly show differentiation between mungbean genotypes. It appears that the effect of mungbean genotypes is mainly on mungbean yield rather than on maize yield. It also appears that there are three groups of mungbean genotypes, one genotype being by far the lowest, namely local Jambe Gede.

As the effect of interaction between upland rice genotypes and locations in the combination of experiments 26, 27 and 28 was significant then the only appropriate procedure is to compare this interaction effect rather than the main effects (Fig. 5.2). From Fig. 5.2, it appears that the distributions of the mean points of upland rice genotypes effects between three locations are entirely different. Upland rice genotypes at Tulang Bawang influence both maize and rice yields. At Baturaja the influence is mainly on the maize yield, while in Way Abung it is on the yield of rice.

In Fig. 5.3, the effect of interaction between row direction of plantings and seasons of combination of experiment 10 and 11 is presented. Again, the significance of interaction effects appears from the four mean points that in fact do not form a rectangle. The row direction of planting gave different responses in the two seasons. For the rainy season, there was no significant difference between the two planting directions, but there was a significant difference between the directions in the dry season.

The results of the combined bivariate analysis of experiments 22 and 23 are presented in two figures (Fig. 5.4a and 5.4b), with different angles for the skew axes as the two effects arise from different strata (i.e. error a and error b in a Split Plot design). From Fig. 5.4a it appears that the effects of maize genotypes in two locations are different. At Trenggalek the mungbean yields are higher and the maize cv. Madura local shows the highest yield of maize while at Bogor, this genotype is the lowest one. This presumably occurs because the cv. Madura local is well adapted to dry areas (such as Trenggalek) as the original cv. Madura local comes from the dry island Madura (Anonymous, 1980a). On the other hand, Bogor is wet so the maize cv. Madura local does not perform as well as the other improved genotypes (i.e. cv. Harapan, cv. Kretek and cv. HPH-68). The other interaction of location occurs with the maize leaf cutting treatments (Fig. 5.4b). The four mean points seem to form a rectangle, but the position of leaf cutting treatments swaps around in those two locations. At Bogor, the yield of maize is higher without leaf cutting while at Trenggalek the highest yield can be got by leaf cutting. This result shows that the physiological response of a crop is different over different environments.

From these results, the best cropping system in one place and season will not always be best for the other places and seasons. The different cultivation or management practices may also yield different rankings of genotypes or treatment combinations in intercropping, as can be seen in the differences of maize and soybean or peanut intercrop and maize and mungbean. Again, the effects that involve intercrops are complex, not only from the locations and seasons, but also from the other crop in that system and even the interaction of those two crops to the environmental conditions.

It has been mentioned earlier that one of the main reasons for growing intercrops is the greater stability in yield over different environments. To examine the yield stability in sole crop versus intercrop, the coefficients of variation for those two cropping systems were calculated (Table 5.8). The coefficient of variation in intercropping systems discussed in Section IV.2 will be reproduced for comparison with the coefficient of variation of sole crops. From Table 5.8, the calculated coefficients of variation of crops in sole crops and intercrops (i.e. each crop analysis) suggest that variability of crops is larger in intercrops rather than sole crops.

This result is perhaps in conformity with the cropping systems and environment interaction results. Thus, it could be argued that mixed cropping has not increased yield stability directly, i.e. by decreasing the coefficients of variation of sole crop yields. Is the combined crop yield then more appropriate for examining intercrop variability? This is not certain, but we shall use it cautiously. From the coefficients of variation of the Land Equivalent Ratio or the first crop yield equivalence of intercrops, it appears that in general the coefficients of variation are lower than sole crops. This results shows that the declining yields of one crop are compensated for by the yields from the other crop. Returning to the coefficients of variation of sole crops and each crop analyses and examining the different cropping combinations, one finds that in general intercrops of maize and soybean are more variable than maize and peanut. This result can also be compared with the result of the regression technique below.

To examine the yield stability of sole crops versus intercrops by regression techniques is only possible for intercrops of maize and peanut or soybean as most experiments involving maize and mungbean intercrops excluded sole crop treatments. It appears that the interaction between cropping systems or intercrop treatments and environments cannot be ignored. To overcome this difficulty, the data were transformed to ln(X + 1) before being subjected to regression analysis (Bartlett, 1947; Tukey, 1949; Freeman, 1973).

Tables 5.9 and 5.10 present stability parameters for fitted regression using different environmental mean yields of maize and peanut or soybean intercrops. From Table 5.9, it appears that the coefficients of regression are lower for the combined yield of intercrop than either sole maize or sole peanut across six methods of calculating the environmental mean. On the other hand, from Table 5.10, it appears that the regression coefficients for the combined intercrop yields are higher than for either sole maize or sole soybean. Thus, it seems that intercropped maize and peanut are more stable than the sole crops, while intercropped maize and soybean are less stable than sole crops. However, the combined intercrop mean yields are in general higher than their component sole crops over environments (Fig. 5.5a to f and 5.6a to f). Therefore, it can be concluded that the intercropping systems are more stable than sole crops. From Figures 5.5 and 5.6, though with different environmental yields the combined intercrops and their component sole crops are not entirely different, the more genotypes or treatments are used to calculate the environmental effect, the more accurately the environment effect will be assessed (Freeman and Perkins, 1971). For example, using sole maize on sole peanut or sole soybean as a standard and regressing the other treatments on that standard we cannot examine those systems together with the sole crop that is regarded as a standard. Therefore, the environmental mean yields should include all the cropping systems involved in those experiments. However, as the yields of the crop are different in intercrop, then the regressions on the actual yield might not be appropriate. This result can be seen in Figure 5.6e where the combined intercrop yield is lower than sole maize when the environmental mean yield is $\leqslant 2.00$ and this situation will be worse when the two crop yields are very different, such as cassava and soybean or mungbean or peanut. Therefore, the more appropriate one is the use of the relative yield only, since the combined yield in terms of the first crop yield equivalence is affected by the market situation.

It was emphasized in Section IV.2 that experimenters tend to be interested not in comparing intercrop and sole crop but in comparing between intercrop treatments.

The adaptation of the regression technique will be use to examine the stability parameter between intercrop treatments on the transformed scale ln (relative yield + 1). The repeated experiments involved intercrops of maize and soybean or mungbean or upland rice for different locations and seasons.

In Table 5.11, we give the stability parameters for fitted regression of 11 soybean genotypes intercropped with maize. Examination of the coefficients of regression shows that the responses of soybean genotypes to environmental change vary. Taking the coefficient of regression and the overall mean yield, we may examine in more detail four superior soybean genotypes (Fig. 5.7). From that figure, it appears that genotypes 2 and 6 can be described as genotypes with greater resistance to environmental change while genotypes 7 and 11 are genotypes with increasing sensitivity to environmental change. The behaviour of those four genotypes and the other genotypes can be taken a step further by plotting the overall mean yield and the regression coefficient to provide a comprehensive measure of performance of the individual genotypes (Fig. 5.8, a Finlay-Wilkinson diagram). From this figure, it appears that the mean yield of genotype 2 is greater than the others and is stable over all environments. Genotype 6 might be the alternative genotype that might be expected having average stability and high yield over environments.

The regression lines for eight mungbean genotypes that are intercropped with maize appear in Fig. 5.9 to show different responses of genotypes to the environmental conditions. Examining that figure together with Table 12, one sees that genotypes 5 and 8 may be described as genotypes specifically adapted to high yielding environments while genotypes 3 and 4 are well adapted to low yielding environments. These stability parameters can be examined in more detail by plotting the coefficients of regression and the overall mean yield of mungbean genotypes (Fig. 5.10). From this figure, it appears that genotypes 1, 2 and 6 might be considered desirable with genotype 1, the most stable and highest yielding over environments.

The regression lines of 10 upland rice genotypes that are intercropped with maize appear in Fig. 5.11 and the stability parameters from the regressions can be seen in Table 5.13. By examining Fig. 5.11 and Table 5.13 together and plotting the regression coefficients with the overall mean yield (Fig. 5.12) one sees that genotypes 1 and 7 might be expected to be desirable genotypes. These two genotypes can be described as genotypes with average stability (i.e. the regression coefficients close to 1.0) and higher than average mean yield over environments.

The other method of examining yield stability between cropping systems is the calculation of the risk of combined intercrop yield below a given disaster level. The relative stability of sole crop and intercrop can be seen in the result of probability of the maize yield equivalence (calculated using price of crops at harvest time) falling below 2.0 tonne per hectare (Table 5.14). Analysis within sole crops suggests that sole mungbean gives the lowest probability of maize yield equivalence falling below 2.0 tonne per hectare and sole maize gives the highest probability. Comparing the intercrops and their component sole crops, one finds that intercrops give lower probability of failure than sole crops. From Table 5.14, it also appears that even in intercropped maize and upland rice the probability of failure is still lower than sole maize. Hence, compensation might also be expected for non-legume intercrops.

The comparison between intercropping systems can be made in more detail by considering a given different disaster level of the maize yield equivalence (Fig. 5.13). From this figure, it appears that maize and peanut or mungbean in general gave the lowest probability of failure while maize and upland rice intercrops gave the highest probability of failure.

As was shown in Section IV.2, analysis using the economic value as given by the maize yield equivalence is affected by market fluctuations. The highest treatments according to the crop price at harvest time could be the lowest in the next season or year. Therefore, we should examine the yield stability of those four intercrops by considering the risk, but without allowing for the effect of market situation on the relative yield (Fig. 5.14). From Fig. 5.4, it appears that intercropped maize and peanut in general give the lowest probability of failure in terms of the relative yield and intercropped upland rice and maize the highest. Figs. 5.12 and 5.13 show slightly different results in ordering of yield stability of maize and soybean or with mungbean intercrop. Again, we should emphasize that the ordering of Fig. 5.13 might change according to the price of the component crops while Fig. 5.14 would not change because of the market situation.

4. DISCUSSION AND SUMMARY

The result of correlations for yield and rank between sole crops and intercrops are not consistent for different crops and even for the same crop across the intercropping systems. The sole crop breeding programme gives the appropriate crops to use for intercropping if there is a high positive correlation between the sole crop and the intercrop systems (Francis, 1980); for example, for maize in a maize and peanut intercrop, for maize in a maize and soybean intercrop and for mungbean in a maize and mungbean intercrop (see Table 5.1). However, for the other crops that show nonsignificant and even negative correlation such as maize intercropped with mungbean, soybean and peanut intercropped with maize or sugarcane, there is more urgency to evaluate and select genotypes separately for the two cropping systems. The lack of consistency of the performance of these genotypes or crops across the cropping systems is influenced by the complex situation in intercrop situations. The obvious factor is the differential behaviour of the genotypes themselves. As the population pressure in intercrop is higher than sole crops, then for genotypes that are density dependent the highest yield in sole crop would not always be seen in intercrops as well. Soil fertility might also be involved as it appears from Section IV.1.2 that under good soil conditions cooperation might be expected while under poor conditions competition could occur. As was also emphasized, by Hayes (1922), low correlation could be expected whenever the expression of a genotype was strongly affected by the microenvironment. Hence, breeding programs for sole crops will not always be appropriate for intercrops as well. This has also been concluded by Francis (1980) and Gomez and Gomez (1983) who emphasized that genotypes and cropping systems interactions were not consistent. The strategy for selection, in the presence of density-dependent natural selection, will involve selection or evaluation under high density of the sole crop. This may be appropriate for developing genotypes in intercropping systems.

In fact, involving different cultivation or management practices in intercrops may also yield different results, even for the same cropping combination. It can be seen that the complex situation in intercrops will be much more evident under different environmental conditions. Interaction between genotypes or sole crops or intercrops cannot be neglected, in view of some negative correlation between cropping systems under different environments.

The interactions between intercrop treatments and environments are given in more detail in the combined bivariate analyses. In general, in the experiments that are repeated either in different locations or season, at least one set of intercrop treatments shows strong interaction with environments. Again, by this result, it appears that intercropping systems and environment interactions cannot be ignored and even intercrops themselves are more complex than sole crops. The repetition of the same experiments over locations and seasons will be useful in deciding which cropping combinations or cultivation practices shows better performance under a wide range of environmental conditions.

Although this study is limited either in season or location, the results support the finding of Francis et al. (1983) that the breeding program for intercrops must also involve not only cropping combinations but also the range of intercropping patterns in which the genotypes will be used.

Most people argue for the importance of a quantitative measure of yield stability between intercrops and sole crops, but there have been few experiments designed to solve the problem. Therefore, the only current way to solve the problem is by considering the same cropping combination over a wide range of experimental structures. Coefficients of variation are lower for LER and first crop yield equivalence than for sole crops. This result also is in conformity with those of the regression analysis for intercropped maize and peanut or soybean. Though in intercropped maize and soybean the regression slope of the combined intercrop yield is greater than either sole maize or sole corn, the means of intercrop yields are consistently higher over all environments. As has been emphasized earlier, by yield stability we mean that the cropping systems show the expected yield over a wide range of environments. We do not mean the cropping systems that show greater yield advantage under stress than non-stress (Rao and Willey, 1980). The interpretation of regression analysis involves both the regression coefficient and the overall mean yield in describing the yield stability from the agronomic point of view (Finlay and Wilkinson, 1963 and Becker, 1981).

Deciding which cropping system should be used to calculate environmental mean yield opens several discussions regarding either the first or second sole crop as a standard and regressing the other cropping systems on that environmental mean yield was a valid approach in terms of the independence of environmental effect. However, the comparison of intercrops and sole crops that is regarded as a standard is not straight forward. As the yields of the component crops in intercrops are different, using the actual yields for calculating environmental mean and regression analysis across those cropping systems is not appropriate. Therefore, substituting the actual yield by the relative yield would be more appropriate (Rao and Willey, 1980). Again, as this analysis only involved three cropping systems, assessment of environmental mean effect may not be appropriate (Mead and Rilley, 1981). In fact, this problem can be reduced by having the same experiments with different genotypes in sole crops as well as in intercrops repeated over a wide range of environments, in order to evaluate yield stability between each genotype or the average genotypes in sole crop and each cropping combination or the average of cropping combination in intercrops. With this type of experiment, the environmental mean yields could be assessed more precisely across the genotypes in sole crops and intercrops.

In fact, our idea in intercropping experiments would be to find the intercrop treatments that show the consistency performance over a wide range of environmental conditions. By using the regression technique, we might distinguish the yield stability between genotypes under association with the other crops in precisely designed experiments. The stable genotypes are described with the coefficient of regression close to 1.0 and high yield over all environments.

The results of considering the probability of suffering a disaster level of maize yield equivalence support those of the other methods: all show that intercrops are more stable than sole crops.

Comparison between intercropping systems shows that intercropped maize and upland rice are more variable than intercropped maize and legumes, possibly because of nitrogen fixation by the legumes.

The methods appropriate for assessing genotypes or cropping systems and environment interactions are still uncertain, especially as in sole crops, the development stability analysis is still in progress (Hill, 1975; Mead and Riley, 1981 and Francis et al., 1983). The correlation technique and the computing of coefficients of variation are limited in various ways. For example, if we use the correlation technique, then we might say that a high correlation was indicative of no interaction, but it is possible that a low correlation may be due not to interaction, but to random effects in one or both environments (Backer, in discussion of Francis, 1980). The coefficient of variation is not designed to distinguish the variability of each treatment rather than for all treatmens in the one experiment. As was emphasized in Section IV.2, bivariate analysis is powerful in detecting differences between intercrop treatments but not for estimating the treatment means. Further, it is difficult to compare between sole crops and intercrops if it is desired. The regression technique on the relative yield provides information additional to that from the bivariate analysis of variance and also takes into account the comparison of sole crops versus intercrops.

This linear regression technique, however, has its own limitations (see Hill, 1975), as the X variates are not independent (Freeman and Perkins, 1971) and the responses of genotypes or cropping systems to environments are not simply linear (Knight, 1973) though by transforming the data to a different scale such as logarithms it is often possible to induce linearity (Finlay and Wilkinson, 1963; Hill, 1975). Whatever the arguments against the linear regression, it has been usefully applied to a number of different crops and other plant species in sole crops (Hill, 1975) and in intercrops (Francis, et al., 1978a, 1978b and Rao and Willey, 1980). Like the other methods, the regression technique will sometimes fail (Hill, 1975). Furthermore, conclusions are limited to the sample of genotypes or cropping systems and environment used in the experiment (Freeman, 1973; Mayo, 1980). Again, as concluded in Section IV.2, if we do not know the appropriate indices for combining intercrop yields, the problem may not be soluble either. The relative yields that were used in regression techniques take into account the simultaneous yield of the first and second crop together, while the bivariate analysis display the two crop yields in terms of means of different intercrop treatments. Therefore, by using regression technique and bivariate analyses together, we may be able to draw comprehensive and relevant conclusions.

The relative merit of the risk method will have to await further investigation since the use of the price of crops in combining yield is subject to the market situation, though the use of relative yield can also be used to compare between intercropping systems.

As has been emphasized, though this study is limited by the availability of data, the results have the merit of merging the study of cropping systems or cropping combination and environment interaction. The study should be concentrated on assessing the best intercropping treatments rather than comparing sole crops and intercrops. This is because our goal in conducting intercropping experiments is not to persuade the farmers to grow intercrops, but to get the best cropping combination or cropping cultivation in intercrops as the farmers recognized the merits of intercrops years ago. This point has also been made by Crookston (1976): "the intercropping system is a new version of an old idea." Again, the important aspect is not to show the yield stability of intercrops versus sole crops, but to distinguish the best treatments among intercropping systems.

TABLE 5.1 Simple correlations for yields and rank orders between sole crops and intercrops.

No. of Expt.	Intercrop	Crop	r	r_s a)	n
6	Maize + Peanut	maize	0.722*	0.567	9
7	" "	maize	0.914**	0.950**	16
		peanut	0.597*	0.485	16
15	" "	maize	0.664**	0.687**	24
		peanut	0.242	0.257	6
16	" "	maize	0.894**	0.727**	12
		peanut	0.288	0.224	12
17	" "	maize	0.816**	0.710**	16
		peanut	0.356	0.304	8
18	" "	maize	0.732**	0.742**	12
19	" "	maize	0.798**	0.755**	12
20	" "	maize	0.950**	0.917**	18
9	Maize + Soybean	soybean	0.032	-0.040	21
12	" "	maize	0.798	0.755	6
		soybean	0.731**	0.729**	18
22	" "	maize	0.680**	0.684**	24
23	" "	maize	0.552**	0.408**	24
24	Maize + Upland rice	maize	-0.007	0.037	27
8	Maize + Mungbean	mungbean	0.796**	0.839	21
13	" "	maize	0.665	0.600	6
		mungbean	0.977**	0.965**	18
14	" "	maize	0.240	0.371	6
		mungbean	0.863**	0.795**	18
39	Sugar cane + Onion	sugar cane	0.527	0.714*	8
40	Sugar cane + Tomatoes	sugar cane	0.600	0.429	8
41	Sugar cane + Maize	sugar cane	0.284	0.285	8
43	" "	sugar cane	0.356	0.435	16
44	" "	sugar cane	-0.495	-0.248	12

a) The Spearman rank correlation

TABLE 5.2 Simple correlations of yields and rank orders across experiments.

Comparison of experiments numbered	Intercrop	Crop	r	r_s	n	r	r_s	n
10, 11	Maize + Soybean	maize	-0.035	0.143	6	-0.284	-0.114	24
		soybean	0.205	0.257	6	-0.105	0.070	24
13, 14	Maize + Mungbean	maize	-0.689	-0.543	6	-0.281	-0.407*	36
		mungbean	0.922**	0.851**	18	0.878**	0.705**	36
22, 23	Maize + Soybean	maize	-0.230	-0.217	24	-0.478*	-0.386*	24
		soybean	+)	+	-	0.243	0.318*	24
26, 27	Maize + Upland rice	maize	-)	-	-	0.365	0.475*	30
		upland rice	-	-	-	-0.119	0.067	30
26, 28	Maize + Upland rice	maize	-	-	-	0.417*	0.409	30
		upland rice	-	-	-	-0.062	0.281	30
27, 28	Maize + Upland rice	maize	-	-	-	-0.093	0.085	30
		upland rice	-	-	-	-0.252	0.216	30

+) number of sample for sole crop is too small (i.e. $\leqslant 6$)

-) no sole crop treatments

TABLE 5.3 Results of the variance-covariance matrices test.

Comparison between experiments numbered	Observed χ^2	df
10 and 11	3.21	3
13 and 14	2.69	3
26, 27 and 28	11.36	6
22 and 23 a)	3.27	3
b)	3.97	3
37 and 38	26.48**	3
50 and 51	25.11**	3

TABLE 5.4 Bivariate analysis of variance of the combination of experiments 13 and 14.

Source of Variation	df	Maize SS	SP	Mung-bean SS	F	df
Seasons	1	34.3301	18.2238	9.6739	7.39*	2, 6
Replicates within seasons	4	4.0592	-1.6772	1.2684		
A-)	1	6.6814	2.8131	1.1844	3.69*	2, 86
B	5	0.5935	0.8494	54.4191	4.35**	10, 86
A.B	5	3.7816	0.3503	1.2492	0.49	10, 86
Seasons.A	1	37.8927	-3.8090	0.3829	15.91**	2, 86
Seasons.B	5	2.5713	-1.2286	4.4616	0.69	10, 86
Seasons.A.B	5	3.7801	0.2667	0.0856	0.37	10, 86
Residual	44	29.4611	-1.2933	4.0636		
Total	71	123.1510		76.7887		

-) A = maize genotypes
B = mungbean genotypes

TABLE 5.5 Bivariate analysis of variance of the combination of experiments 26, 27 and 28.

Source of Variation	df	Maize SS	SP	Upland rice SS	F	df
Sites	2	1026.45	-54.12	498.20	33.17**	4, 10
Replicates within sites	6	64.96	3.15	11.22		
Upland rice genotypes	9	42.99	-6.86	123.05	8.38**	18, 106
Sites upland rice genotypes	18	63.84	26.91	221.71	6.88**	36, 106
Residual	54	114.70	8.55	61.73		
Total	89	1312.94		915.51		

TABLE 5.6 Bivariate analysis of variance of the combination of experiments 10 and 11.

Source of Variation	df	Maize SS	SP	Soybean SS	F	df
Seasons	1	0.0837	0.2403	0.6896	0.30	2, 6
Replicates within seasons	4	2.8253	-0.1944	0.1298		
A-)	1	2.0244	0.1747	0.0151	0.96	2, 54
B	3	4.4059	-0.0594	0.0176	0.68	6, 54
A.B	3	7.6089	-0.0571	0.0043	1.15	6, 54
Seasons.A	1	7.2692	-0.6706	0.0619	3.33*	2, 54
Seasons.B	3	3.3106	-0.3689	0.0738	0.53	6, 54
Season.A.B.	3	2.8518	-0.1348	0.0105	0.45	6, 54
Residual	28	24.5652	-1.2945	0.8242		
Total	47	54.9450		1.8262		

-) A = Row direction of planting

B = Planting distance of maize

TABLE 5.7 Bivariate analysis of variance of the combination of experiments 22 and 23.

Source of Variation	df	Maize SS	SP	Soybean SS	F	df
Sites	1	2.8585	10.9103	41.6433	7.45*	2, 6
Replicates within sites	4	11.2136	0.4243	0.4999		
A-)	3	12.4419	-2.5360	3.5962	2.25	6, 22
Sites.A	3	40.9782	7.5314	2.5357	4.49**	6, 22
Residual a	12	13.0892	1.0638	1.8391		
B	1	0.9049	-0.0602	0.0040	0.42	2, 30
A.B.	3	0.8139	0.0062	0.0948	0.14	6, 30
Sites.B	1	25.3492	-1.3839	0.0756	9.114**	2, 30
Sites.A.B.	3	2.3036	0.3754	0.3709	0.41	6, 30
Residual	16	8.3776	1.5971	1.1895		
Total	47	118.3306		51.8490		

-) A = maize genotypes
B = leaf cutting on maize

TABLE 5.8 Coefficient of variation of sole crops and intercrops for each experiment.

No. of Expt.	Intercrop	Crop	Coefficient of Variation (%) sole crop	Intercrop each crop analyses	combined analyses LER	combined analyses 1st crop equivalenc
6	Maize + Peanut	maize	15.60	17.83	7.90	8.00
7	" "	maize	9.10	14.86	6.30	4.70
		peanut	4.50	2.99		
15	" "	maize	19.90	18.14	18.10	14.70
		peanut	19.10	28.23		
16	" "	maize	10.60	10.20	9.90	10.90
		peanut	8.70	14.00		
17	" "	maize	6.50	5.56	3.80	3.70
		peanut	7.20	4.61		
18	" "	maize	16.00	11.40	18.50	9.70
19	" "	maize	3.90	6.22	4.70	4.50
20	" "	maize	10.30	10.67	16.80	12.90
9	Maize + Soybean	soybean	18.80	15.00	12.90	13.40
10	" "	maize	2.50	11.50	12.70	3.32
		soybean	4.00	30.39		
11	" "	maize	15.80	15.87	10.70	15.00
		soybean	3.80	16.29		
12	" "	maize	4.70	21.41	14.20	12.60
		soybean	17.90	18.14		
22	" "	maize	8.30	7.60	13.20	9.90
23	" "	maize	9.20	12.00	10.80	10.60
24	Maize + Upland rice	rice	12.90	22.20	8.50	8.50
8	Maize + Mungbean	mungbean	5.20	16.70	8.20	7.30
13	" "	maize	6.30	13.77	6.60	6.70
		mungbean	12.70	12.57		
14	" "	maize	13.50	13.77	11.80	12.40
		mungbean	16.70	19.72		

TABLE 5.9 Stability parameters for fitted regressions, using six different methods of environmental mean, for intercropped maize and peanut.

Environmental mean	b					r^2					mean yield (ln(X + 1))				
	Sole crop		Intercrop			Sole crop		Intercrop			Sole crop		Intercrop		
	maize	peanut	maize	peanut	total	maize	pea-nut	maize	pea-nut	total	maize	pea-nut	maize	pea-nut	total
1. Mean of sole maize	1.000±0.000	0.886±0.166	0.851±0.140	-0.148±0.029	0.567±0.095	1.000	0.805	0.620	0.113	0.865	1.302	0.804	1.144	0.686	1.417
2. Mean of sole peanut	0.732±0.020	1.000±0.000	0.164±0.051	0.442±0.049	0.331±0.023	0.805	1.000	0.131	0.373	0.555	1.302	0.804	1.144	0.686	1.417
3. Mean of sole + intercrop of maize	1.414±0.207	0.864±0.126	2.014±0.362	-1.149±0.313	0.931±0.107	0.883	0.490	0.915	0.550	0.931	1.302	0.804	1.144	0.686	1.417
4. Mean of sole + intercrop of peanut	0.607±0.176	1.378±0.200	-0.927±0.274	1.687±0.343	0.104±0.049	0.395	0.814	0.439	0.841	0.504	1.302	0.804	1.144	0.686	1.417
5. Mean of 3 and 4	3.875±0.285	3.669±0.140	3.213±0.277	-0.304±0.094	2.316±0.268	0.984	0.847	0.594	0.109	0.896	1.302	0.804	1.144	0.686	1.417
6. As in 5, but using relative yield	2.662±0.264	4.225±0.164	0.940±0.347	1.640±0.271	1.798±0.232	0.888	0.966	0.241	0.322	0.862	0.689	0.687	0.582	0.587	0.954

TABLE 5.10 Stability parameters for fitted regressions, using six different methods of environmental mean, for intercropped maize and soybean.

Environmental mean	b					r^2					mean yield (ln(X + 1))				
	Sole crop		Intercrop			Sole crop		Intercrop			Sole crop		Intercrop		
	maize	soybean	maize	soybean	total	maize	soy-bean	maize	soy-bean	total	maize	soy-bean	maize	soy-bean	total
1. Mean of sole maize	1.000±0.000	0.980±0.189	1.374±0.169	1.754±0.158	1.878±0.172	1.000	0.918	0.676	0.950	0.872	1.343	0.754	1.245	0.619	1.412
2. Mean of sole soybean	0.860±0.165	1.000±0.000	0.890±0.154	1.600±0.193	1.391±0.154	0.918	1.000	0.462	0.926	0.690	1.343	0.754	1.245	0.619	1.412
3. Mean of sole + intercrop of maize	1.086±0.182	0.918±0.138	2.438±0.139	1.702±0.205	2.689±0.140	0.865	0.684	0.955	0.734	0.993	1.343	0.754	1.245	0.619	1.412
4. Mean of sole + intercrop of soybean	0.984±0.147	1.084±0.103	1.016±9.126	1.883±0.157	1.646±0.176	0.948	0.978	0.482	0.983	0.736	1.343	0.754	1.245	0.619	1.412
5. Mean of 3 and 4	1.637±0.206	1.538±0.133	2.899±0.240	2.791±0.142	3.545±0.412	0.963	0.846	0.839	0.889	0.968	1.343	0.754	1.245	0.619	1.412
6. As in 5, but using relative yield	1.508±0.117	2.227±0.202	2.159±0.127	3.966±0.235	4.205±0.399	0.985	0.927	0.721	0.957	0.978	0.607	0.728	0.607	0.570	0.956

TABLE 5.11 Stability parameters for fitted regressions of intercropped maize and soybean (i.e. ln (relative yield + 1))

soybean genotypes	b	r^2	Mean yield
1. Imp. Pelican	0.937 ± 0.081	0.99	0.996
2. No. 1343	0.758 ± 0.125	0.93	1.2990
3. CKIV.6	0.918 ± 0.067	0.99	0.899
4. No. 1400B	1.006 ± 0.096	0.97	0.990
5. CKI.10	0.872 ± 0.083	0.97	0.936
6. Orba	0.963 ± 0.042	0.99	1.198
7. No. 1682	1.111 ± 0.033	0.99	1.139
8. CKI-11	1.119 ± 0.039	0.99	1.097
9. CKII.34	1.187 ± 0.041	0.99	1.065
10. No. 1667	1.155 ± 0.117	0.99	0.957
11. No. 1920	1.196 ± 0.035	0.99	1.136

TABLE 5.12 Stability parameters for fitted regressions of intercropped maize and mungbean genotypes (i.e. ln (relative yield + 1))

mungbean genotypes	b	r^2	Mean yield
1. No. TM72	0.858 ± 0.159	0.91	1.013
2. No. TM106	1.068 ± 0.159	0.90	0.965
3. No. TM100	0.698 ± 0.173	0.80	0.900
4. No. 438	0.673 ± 0.238	0.73	0.870
5. No. 423	1.445 ± 0.216	0.92	0.872
6. No. 129	1.178 ± 0.160	0.94	1.007
7. Bhakti	1.167 ± 0.123	0.95	0.884
8. No. 467	1.364 ± 0.187	0.50	0.899

TABLE 5.13 Stability parameters for fitted regressions of intercropped maize and upland rice (i.e. ln(relative yield + 1)).

Upland rice genotypes	b	r^2	Mean yield
1. IET.144	1.012 ± 0.222	0.84	0.979
2. Local	1.247 ± 0.073	0.99	0.865
3. IR.36	1.110 ± 0.155	0.93	0.895
4. Gata	1.050 ± 0.093	0.97	0.915
5. IR.206	1.226 ± 0.112	0.97	0.963
6. Bical	0.927 ± 0.209	0.83	0.871
7. No. 981	0.806 ± 0.269	0.75	0.993
8. No. B295	0.793 ± 0.438	0.52	0.820
9. No. GH77	0.833 ± 0.333	0.61	0.923
10. IR.42	0.995 ± 0.402	0.61	0.767

TABLE 5.14 The probability of maize yield equivalence per hectare falling below 2.0 tonne.

Cropping pattern	Mean of maize yield equivalence kg/ha	Probability of maize yield equivalence falling below 2 ton/ha
Sole corn	2573	0.1469
Sole soybean	2964	0.0764
Sole peanut	3031	0.0294
Sole mungbean	3058	0.0164
Corn + soybean	4248	0.0202
Corn + peanut	5035	0.0004
Corn + mungbean	5119	<0.0001
Corn + rice	4248	0.0465

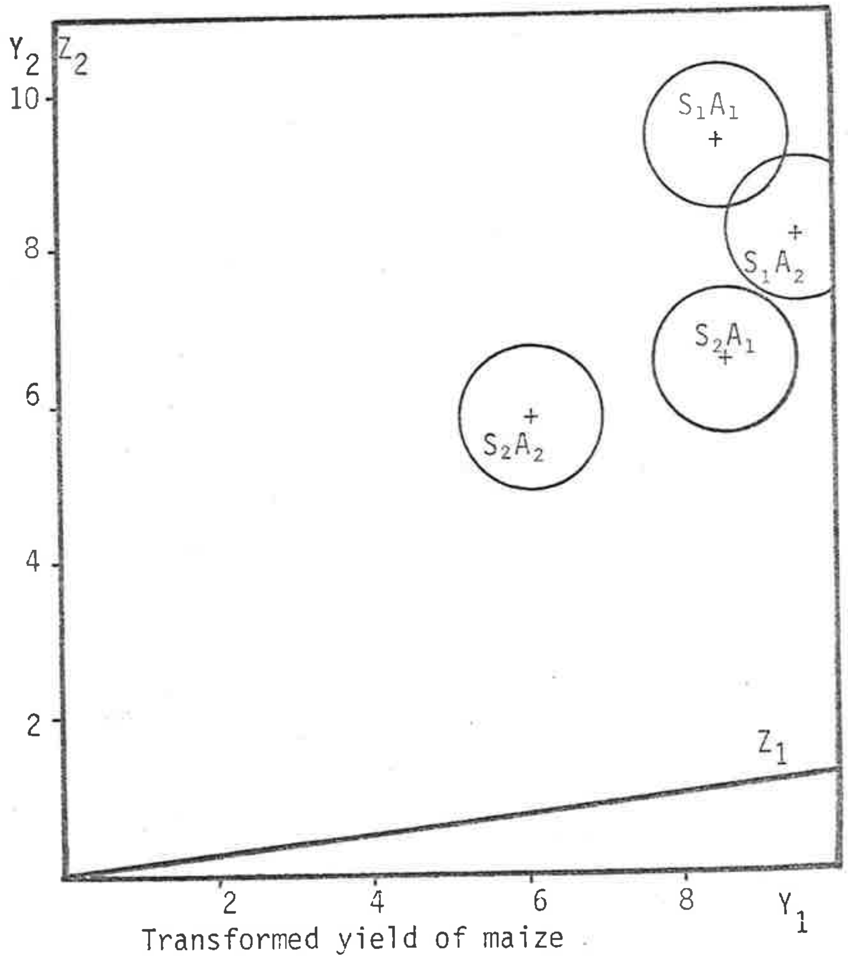


Fig.5.1a The effect of season and maize genotype interaction using the combined results of experiments 13 and 14. S_1 and S_2 are the rainy and dry seasons respectively; A_1 and A_2 represent maize cv.Harapan and cv.Kretek.

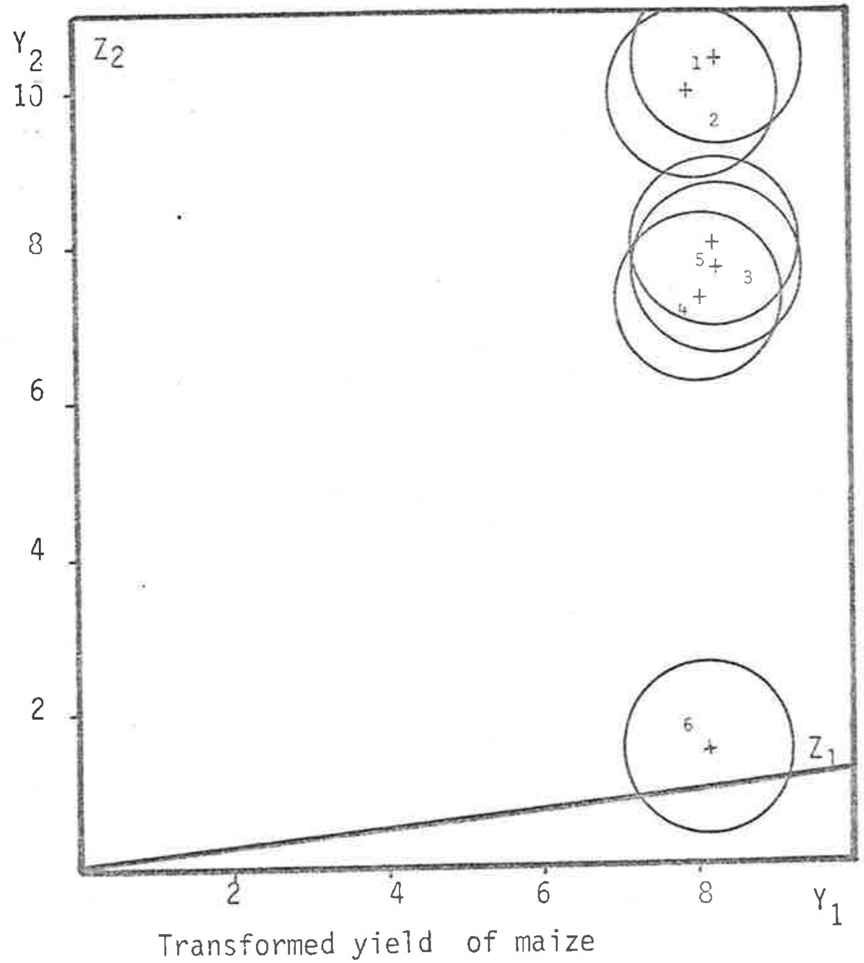


Fig.5.1b The effect of mungbean genotypes using the combined results of experiment 13 and 14. 1 to 6 represent the number of mungbean genotypes.

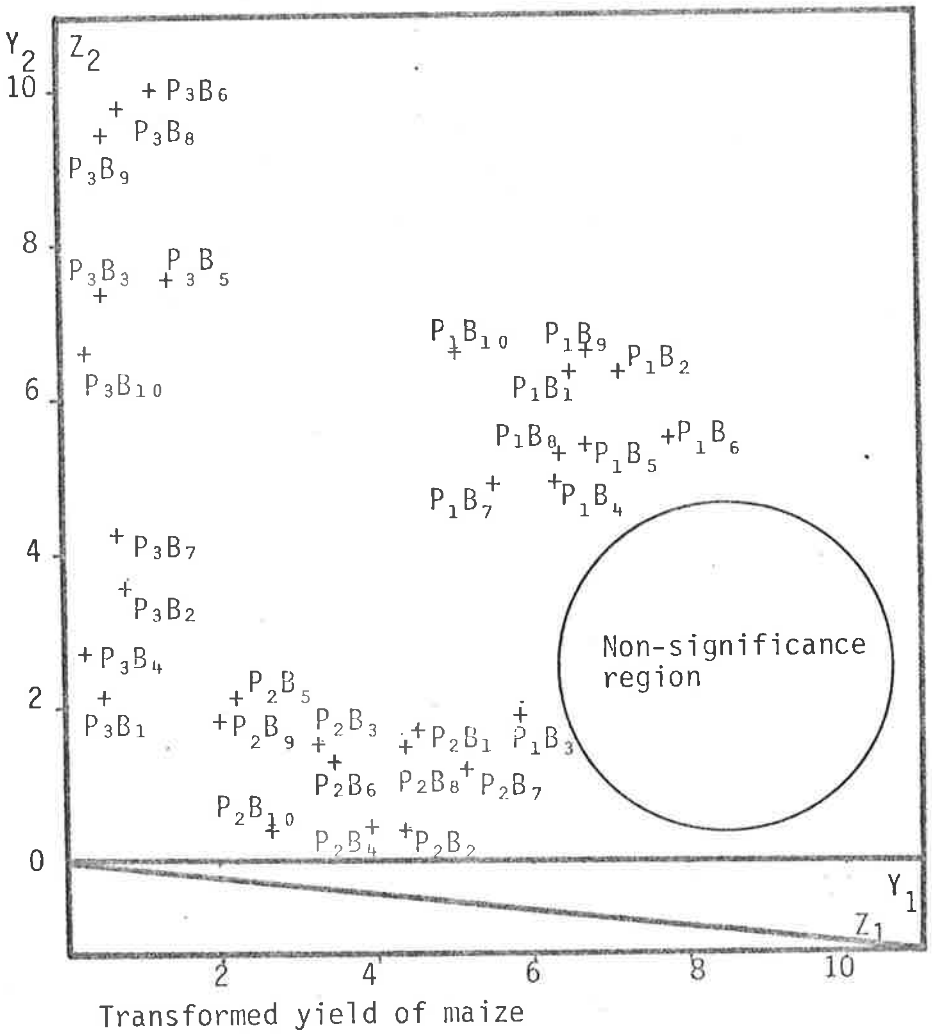


Fig. 5.2 The effect of sites and upland rice interaction using the combined results of experiment 26,27 and 28. P_1, P_2 and P_3 are Tulang Bawang, Batu Raja and Way Abung station respectivelly; B_1 to B_{10} represent the number of upland rice genotypes.

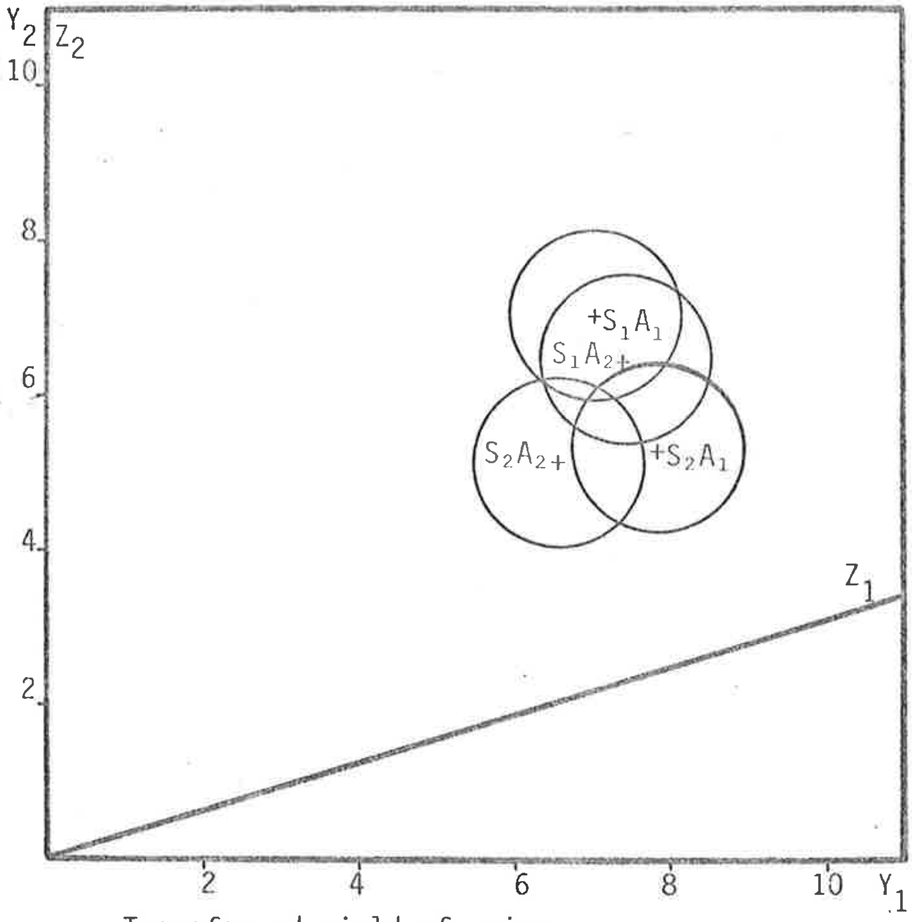


Fig. 5.3 The effect of seasons and row direction interaction using the combined results of experiments 10 and 11. S_1 and S_2 are rainy and dry seasons respectivelly; A_1 and A_2 represent north-south and east-west row direction of planting.

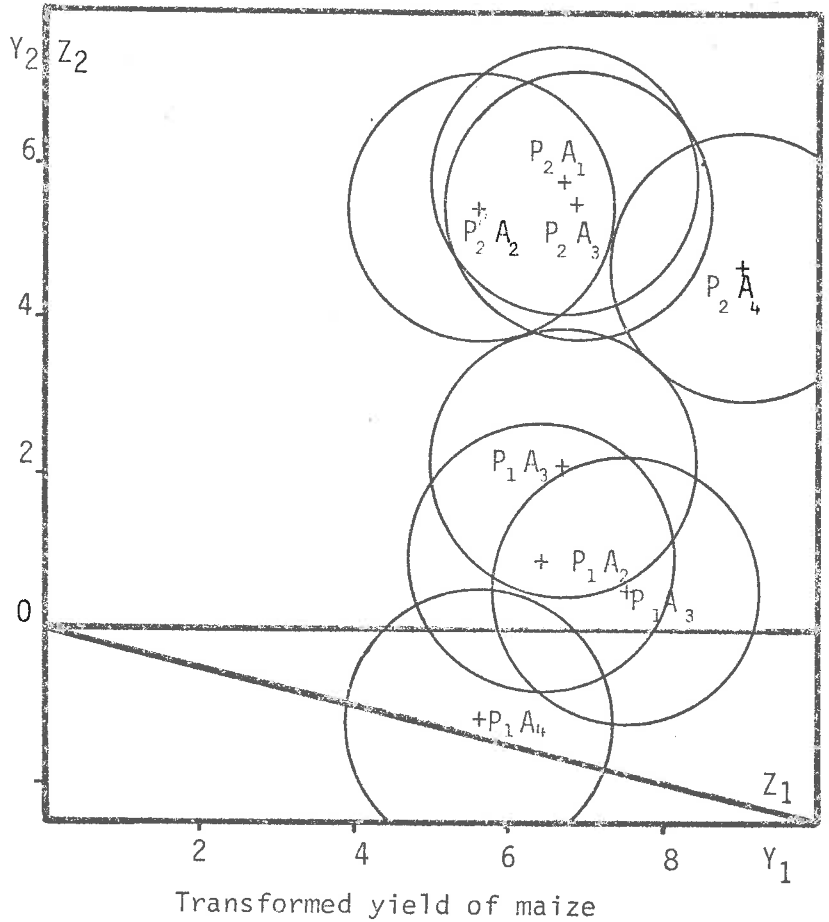


Fig. 5.4a The effect of sites and maize genotypes using the combined results of experiments 22 and 23. P_1 and P_2 are Trenggalek and Bogor station respectivelly; A_i represents maize genotypes.

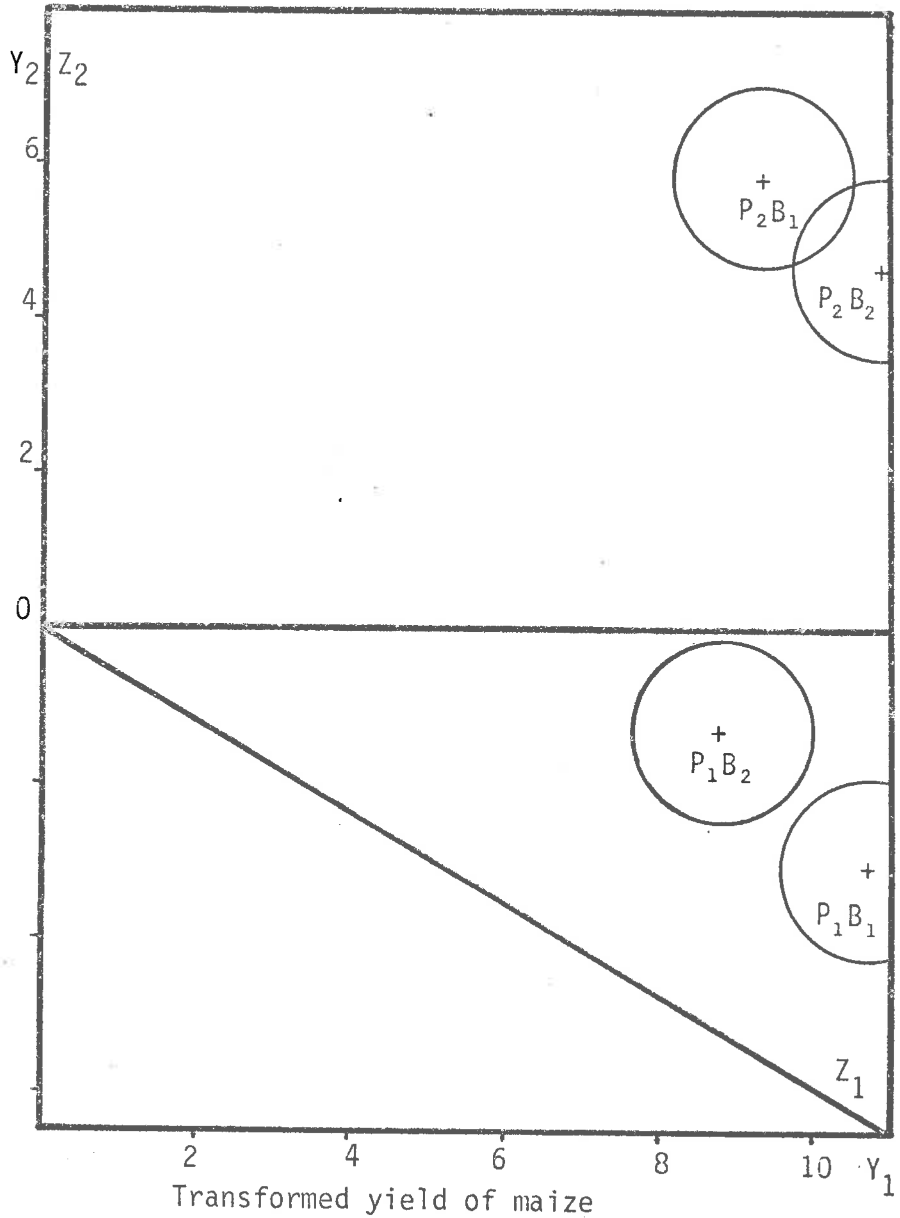


Fig. 5.4b The effect of sites and leaf cutting treatments interaction using the combined results of experiments 22 and 23. P_1 and P_2 are Trenggalek and Bogor station respectivelly; B_1 and B_2 are without and with lef cutting treatments.

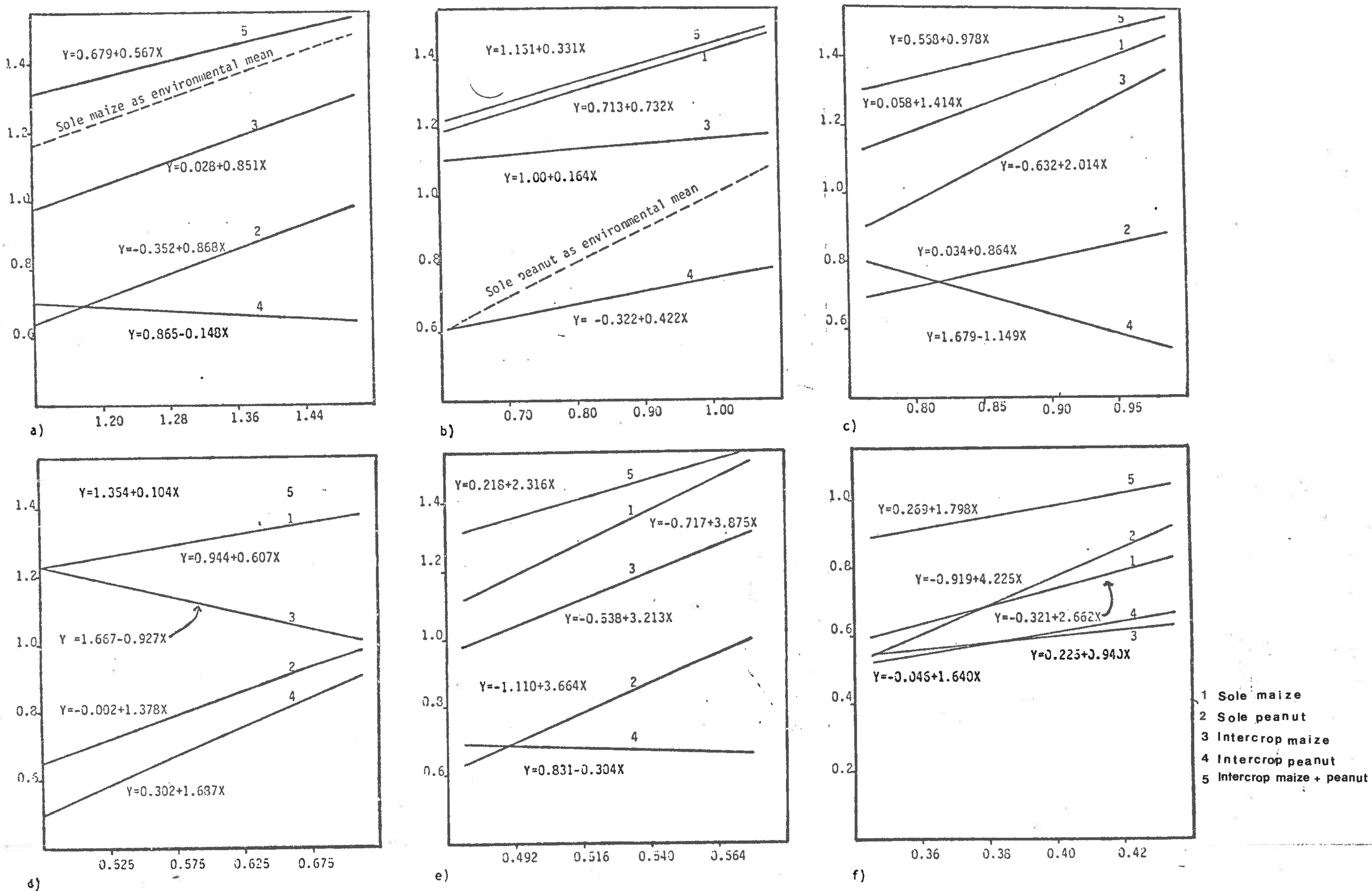


Fig. 5.5 Regression lines showing the relationship of individual cropping systems of intercropped maize and peanut with: a) mean of sole maize as environmental mean; b) mean of sole peanut as environmental mean; c) mean of sole and intercrop of maize as environmental mean; d) mean of sole and intercrop of peanut as environmental mean; e) mean of (c) and (d) as environmental mean; f) as in (e), but using the relative yield. The X and Y coordinates are the environmental yield and cropping systems yield in ln (yield+1).

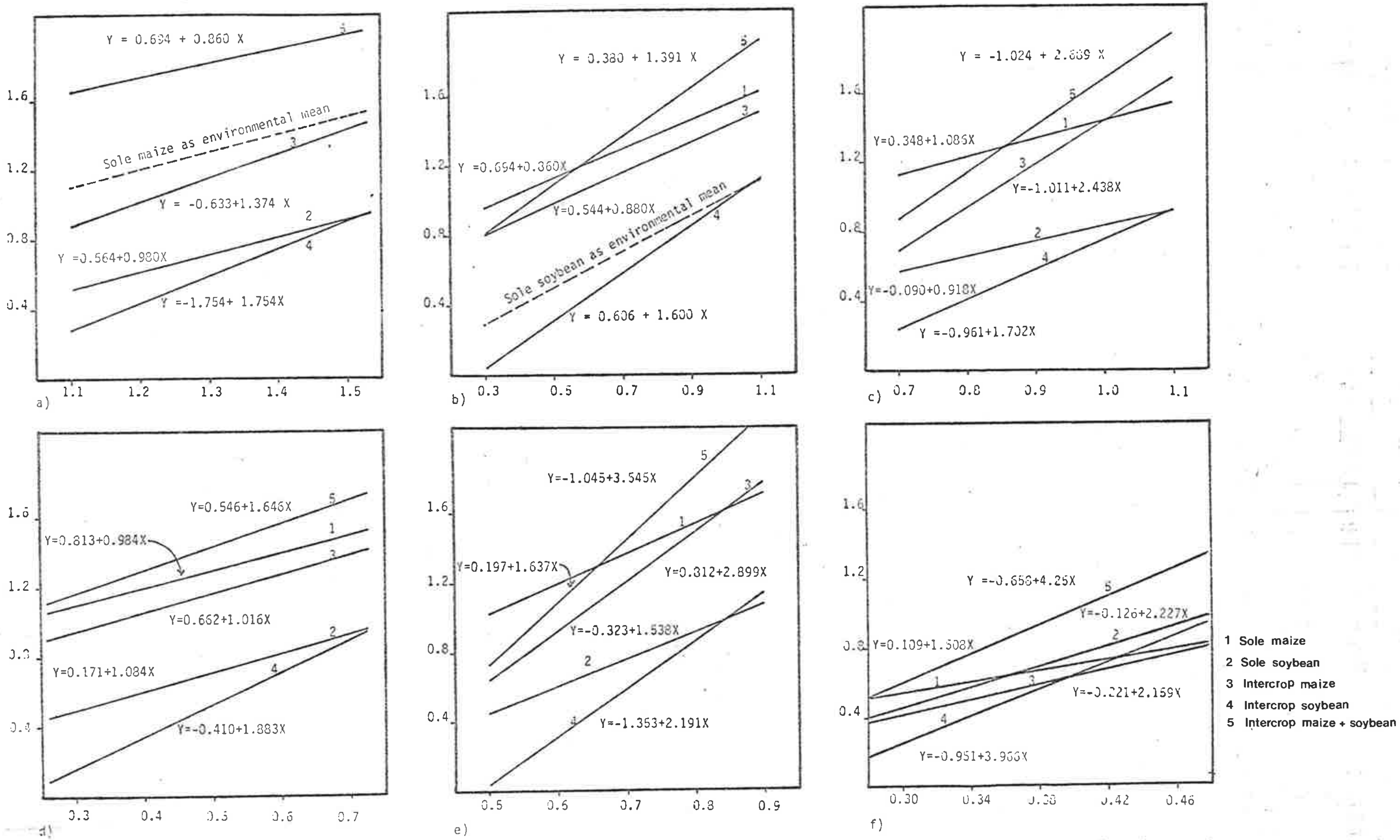


Fig. 5.6 Regression lines showing the relationship of individual cropping systems of intercropped maize and soybean with : a) mean of sole maize as environmental mean; b) mean of sole soybean as environmental mean; c) mean of sole and intercrop of maize as environmental mean; d) mean of sole and intercrop of soybean as environmental mean; e) mean of (c) and (d) as environmental mean; f) as in (e), but using relative yield. The X and Y coordinates are the environmental mean yield and cropping systems yield in ln (yield +1).

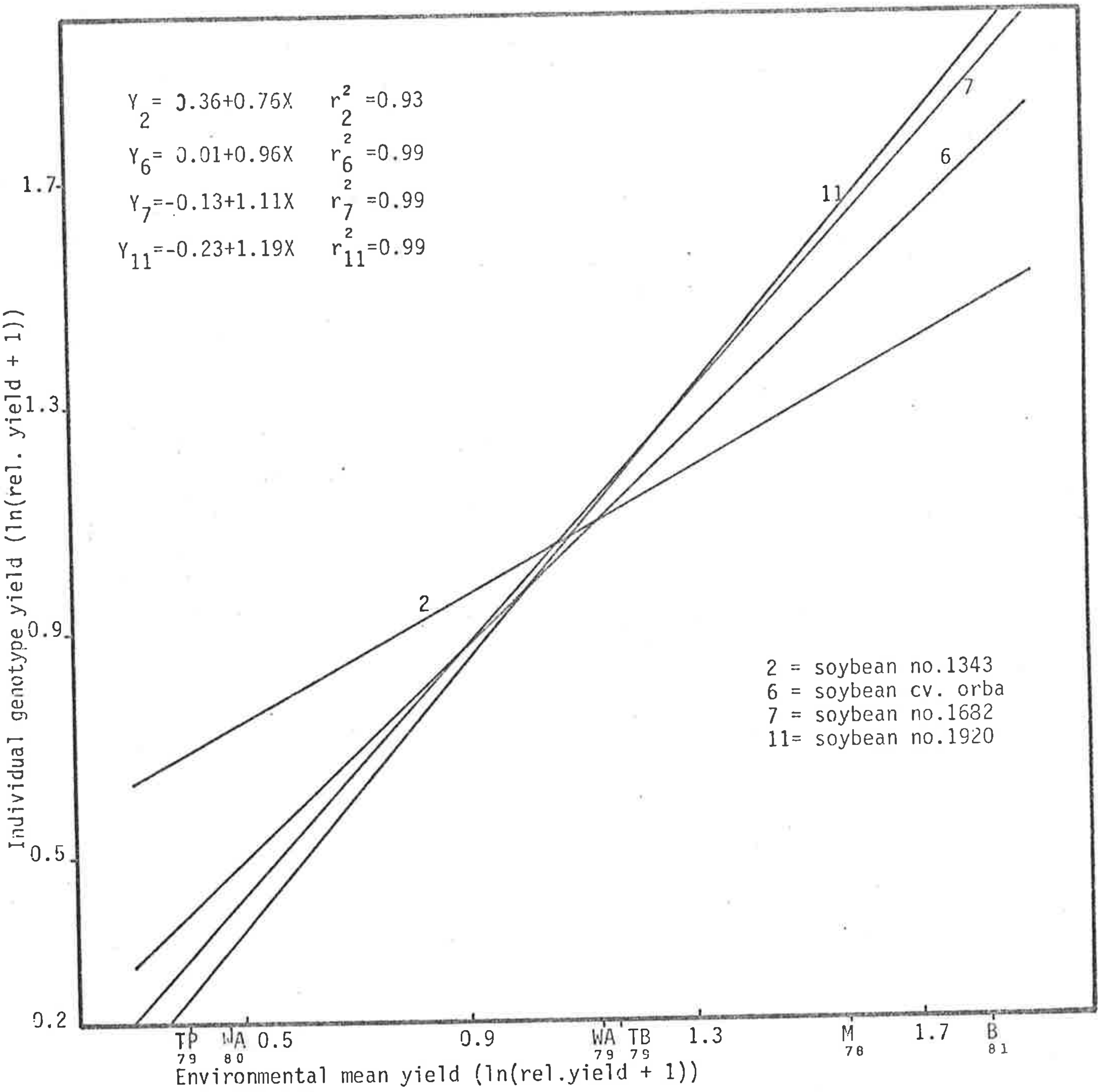


Fig.5.7 Regression lines, showing the relationship of the four best of soybean genotypes which have been intercropped with maize. WA, Way Abung; TB, Tulang Bawang; TP, Tajau Pecah; M, Malang; B, Bogor. 78, 79, 80 and 81 represent 1978, 1979, 1980 and 1981.

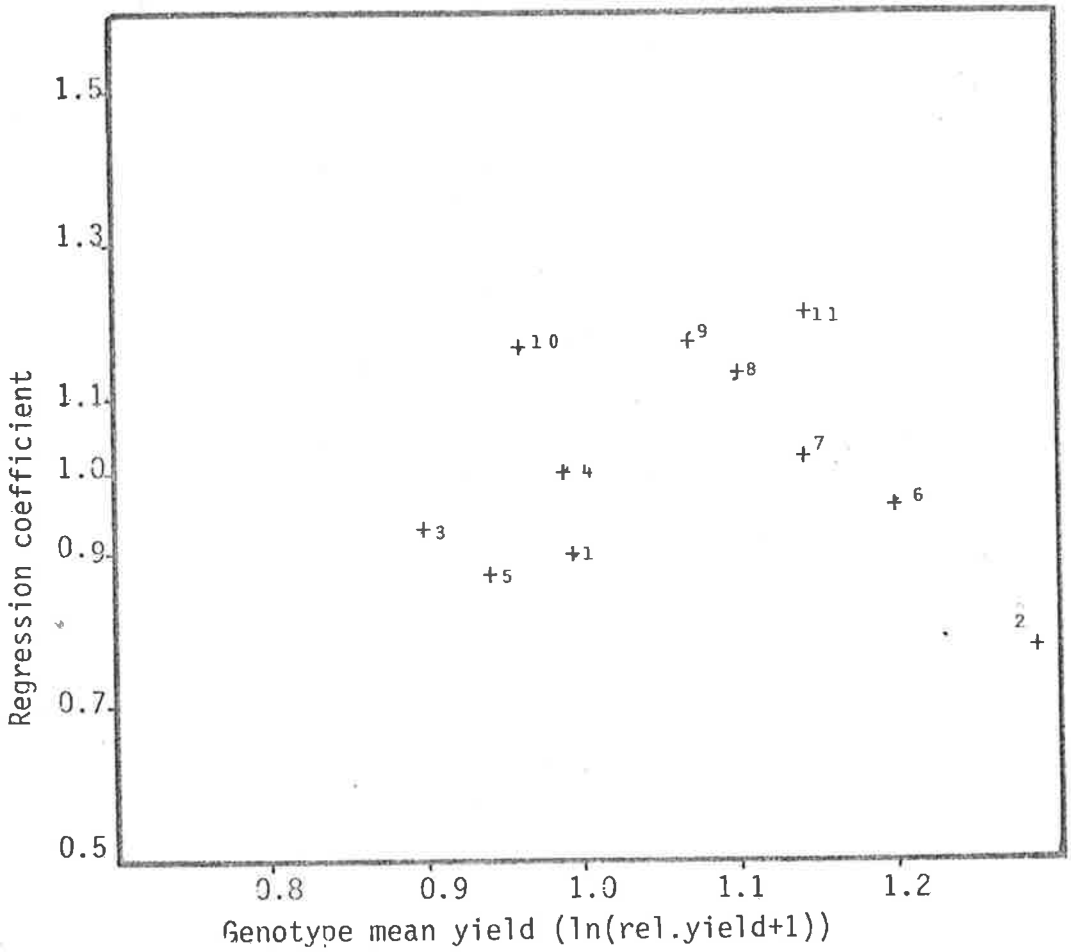


Fig. 5.8 Relationship of regression coefficient and genotype mean yield of 11 soybean genotypes which have been inetrcropped with maize.

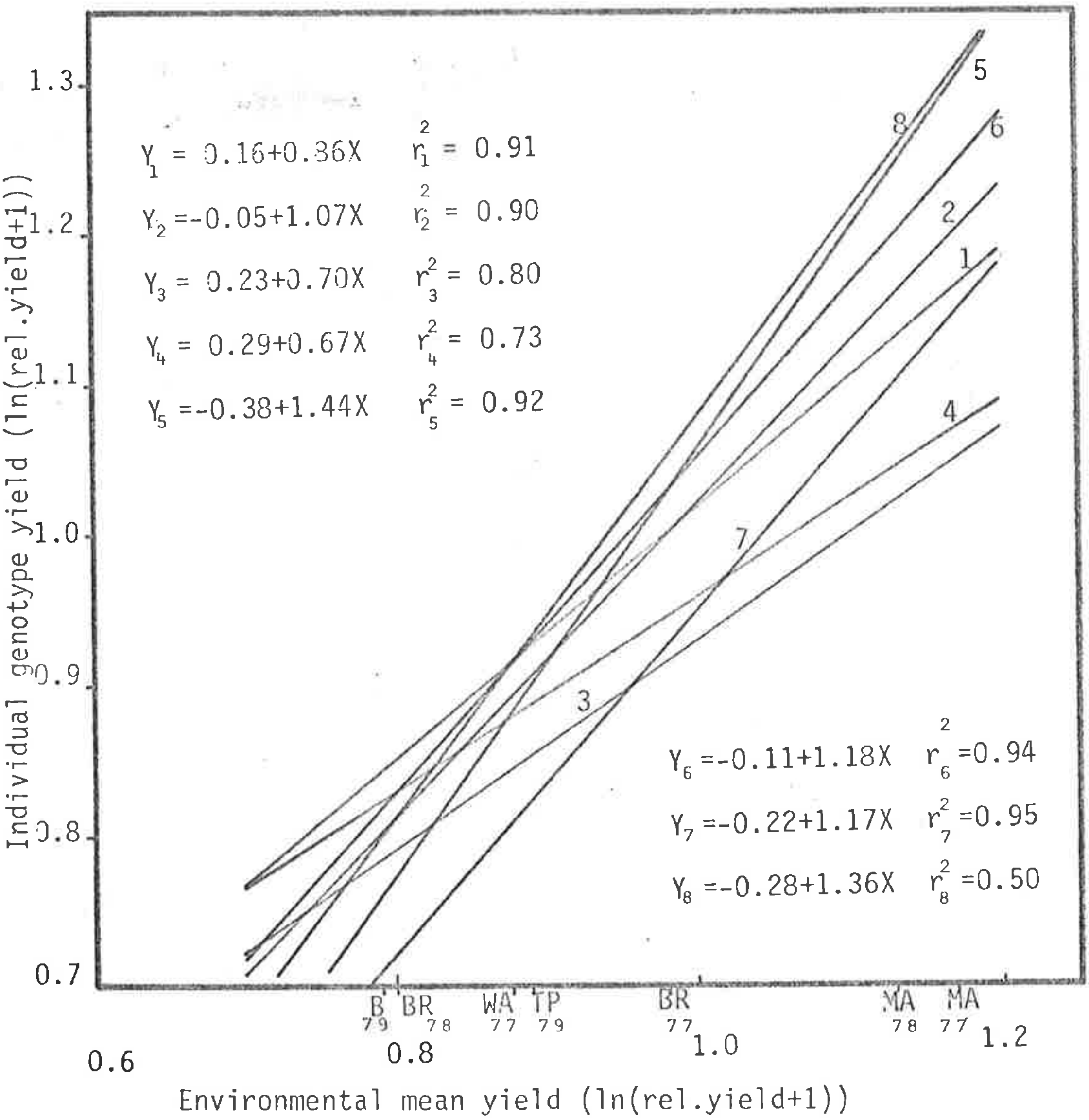


Fig.5.9 Regression lines, showing the relationship of individual yield of 8 mungbean genotypes which have been intercropped with maize. WA, Way Abung; BR, Batu Raja; M, Malang; B, Bogor; TP, Tajau Pecah. 77, 78 and 79 represent 1977, 1978, 1979. 1 to 8 represent the number of mungbean genotypes.

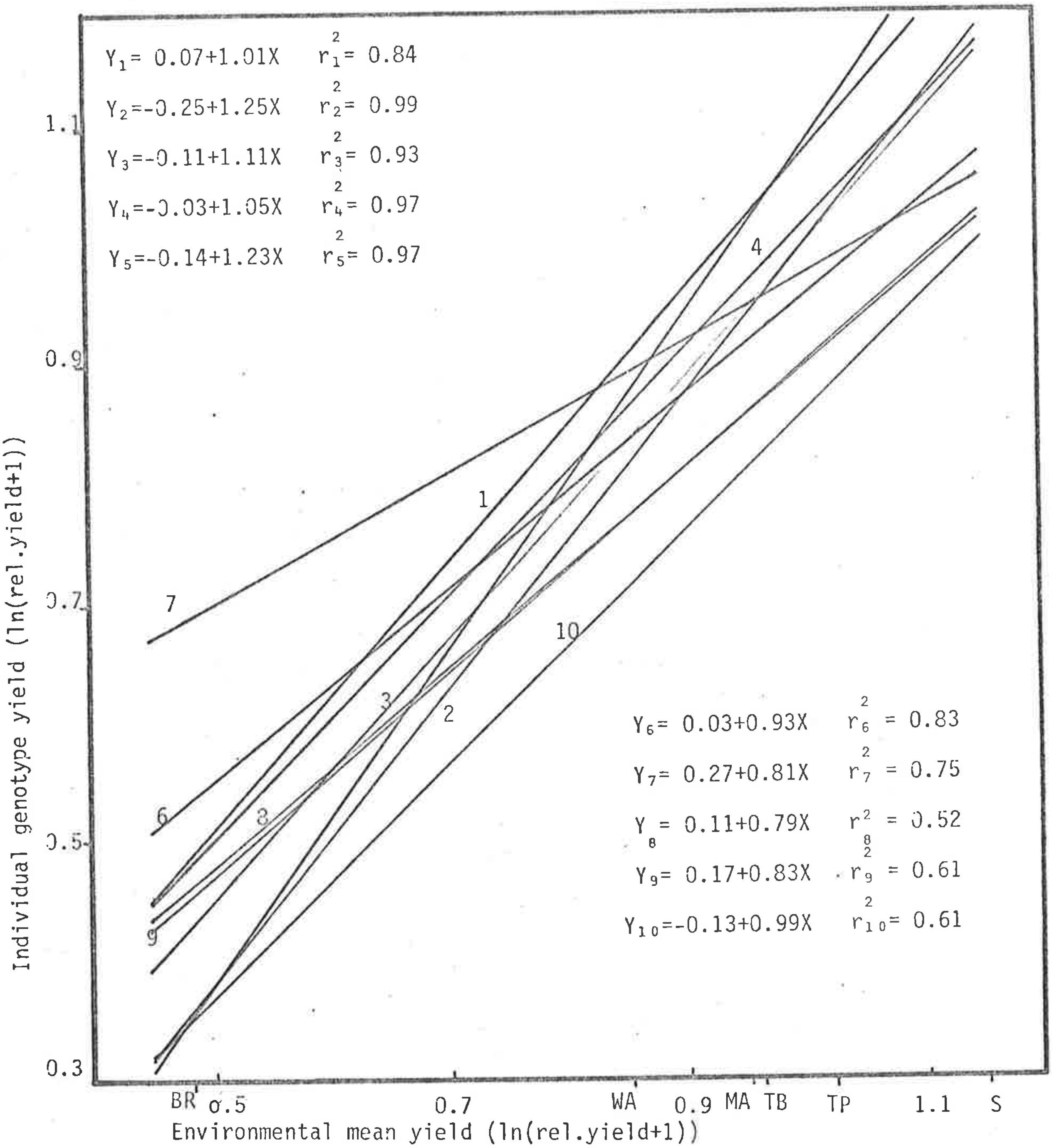


Fig.5.11 Regression lines, showing the relationship of each of 10 upland rice genotypes which have been intercropped with maize. TB, Tulang Bawang; TP, Tajau Pecah; WA, Way Abung; BR, Batu Raja; S, Sukamandi; MA, Madura. 1 to 10 represent the number of upland rice genotypes. All experiments in rainy season of 1979/1980.

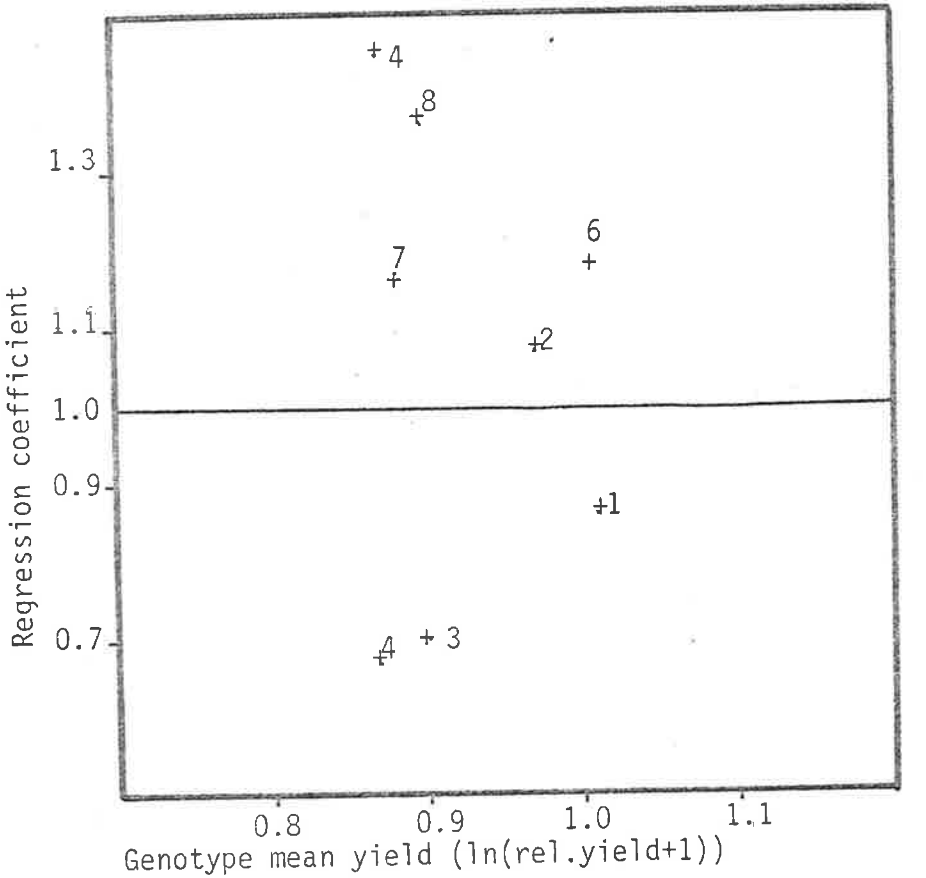


Fig.5.10 Relationship of regression coefficient and genotype mean yield of 8 mungbean genotypes which have been intercropped with maize.

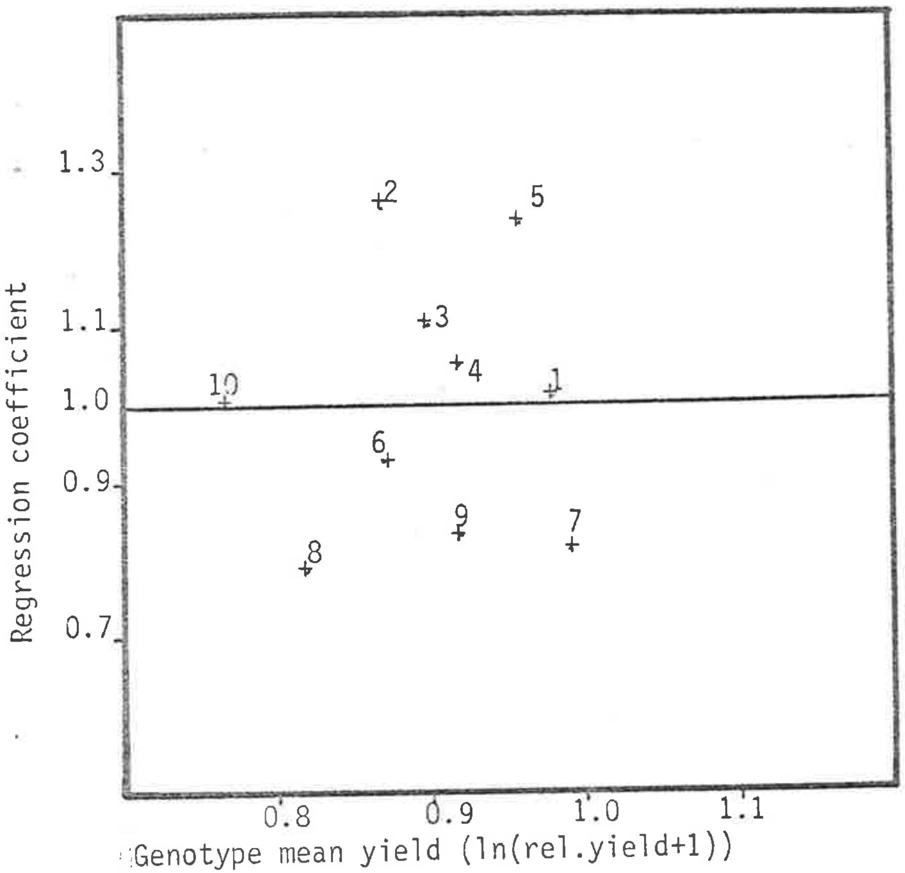


Fig.5.12 The relationship of regression coefficient and genotype mean yield of 10 upland rice genotypes which have been intercropped with maize.

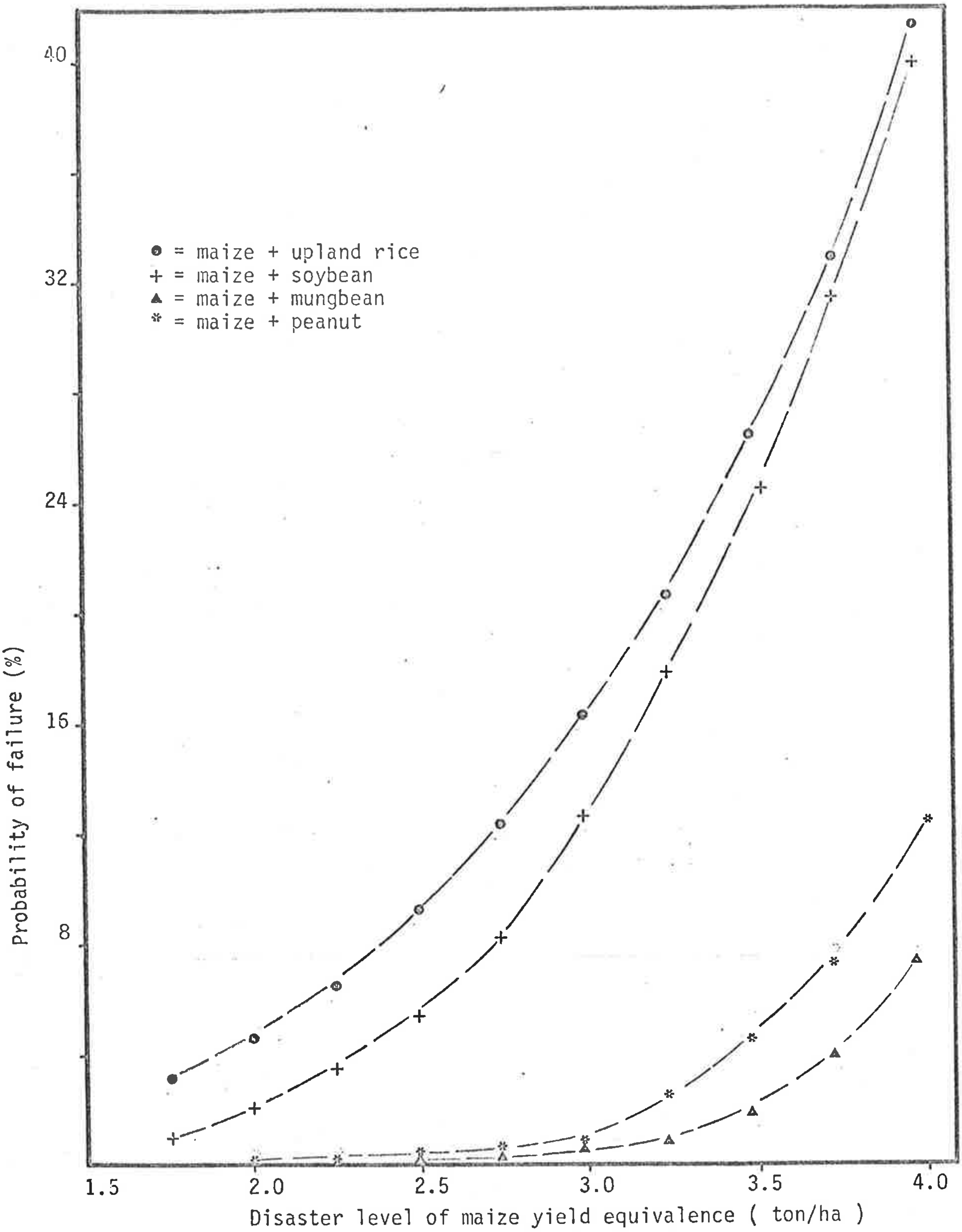


Fig. 5.13 Probability of failure for different intercropping systems at given disaster levels of maize yield equivalence.

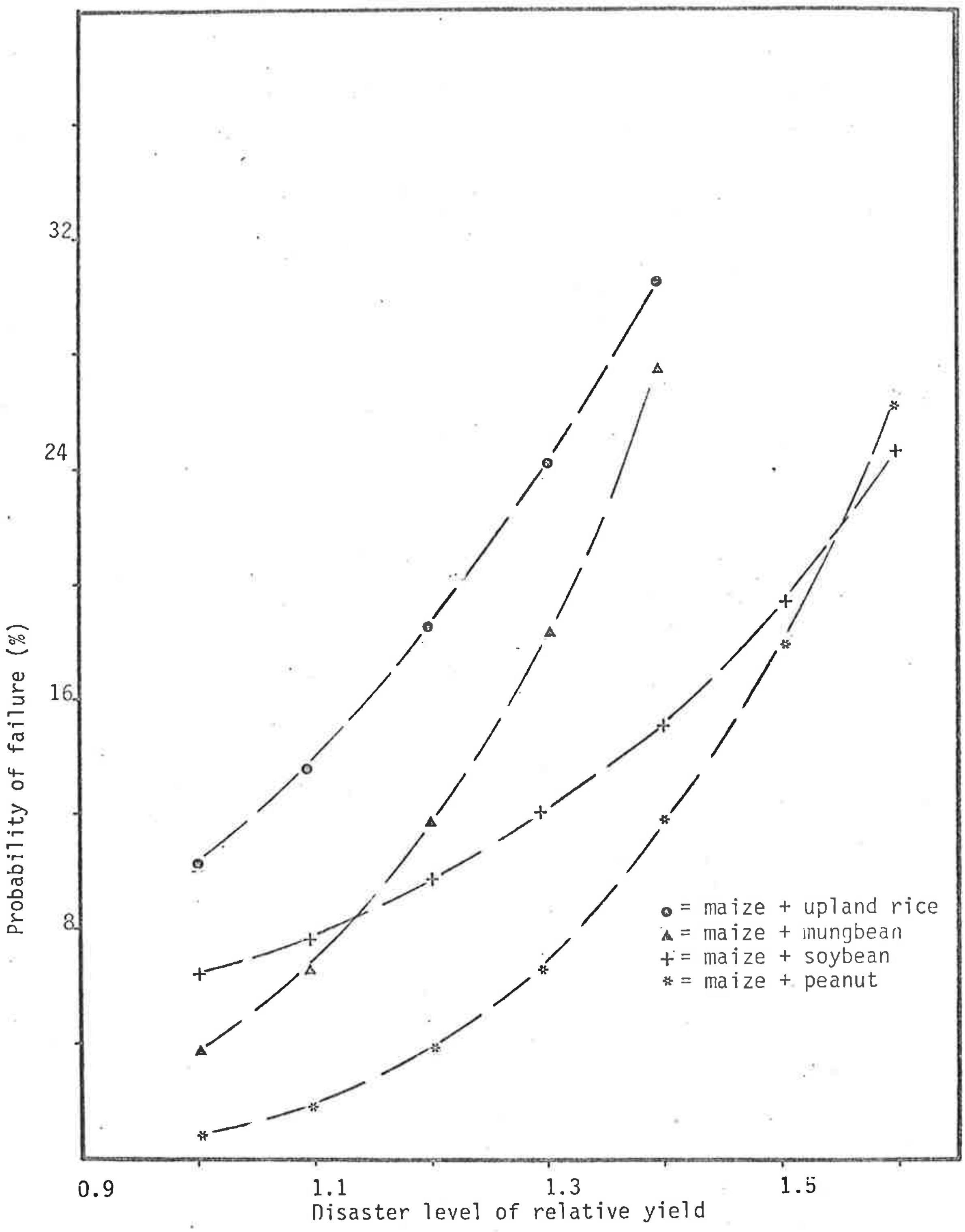


Fig. 5.14 Probability of failure for different intercropping systems at given disaster levels of relative yield.

VI. THE NATURE OF COMPETITION ANALYSIS FOR INTERCROPPING SYSTEMS

1. INTRODUCTION

Most plants, either in their natural habitat or when cultivated will grow or develop under the influence of the proximity of their neighbours (Aspinall and Milthorpe, 1959, Mather, 1961 and Donald, 1963). Milthorpe (1961) emphasized that the proximity of plants to each other is the result of spacing and of size, the latter being determined by the initial captial of growing material such as number and size of embryos and the relative growth rates during the growth time. The importance of these aspects for plant growth have long been recognised by agronomists concerned with (i) the relationship between densities and the yield of crop plants and (ii) an analysis of how the environment changes in response to increasing density (Harper, 1961). The determining growth factors may be direct effects from one plant to another or indirect effects via modifications of the external environment (Aspinall and Milthorpe, 1959). During their growth, plants modify the environment around them and this is of course the environment which influences the neighbouring plants. As a result, the plants and their modified environments interact with each other during growth when this interaction is usually described as competition (Aspinall and Milthorpe, 1959, Donald, 1963, Hall, 1974a, b).

Donald (1963) emphasized that two plants will not compete with each other when their requirements for growth are in excess. The competition between these two plants starts as soon as the immediate supply of one important growth factor falls below the combined demands of those plants. Donald also emphasized that competition will not occur if the environment of one plant is independent of its neighbour. This idea has long been recognised by the peasant farmers as they grow their two or more different crops simultaneously on the same area of ground which is a mixed cropping or intercropping system (Aiyer, 1949). The size of yield advantage of and intercropping system depends on the magnitude of the difference between crops in growth resources requirement and in timing the use of those resources (Snaydon and Harris, 1979). To get the maximum yield advantage in intercropping, there should be some elements of complementarity between the crops in order to minimize the competition between the crops (Singh et al., 1979).

The factors for which competition usually occurs among plants are nutrients, water, light, oxygen and carbon dioxide (Donald, 1958, 1963, Milthorpe, 1961). The relations between these growth factors in determining plant growth are complex (Hall, 1974a). They may be interactive or additive depending on the environmental conditions and plant themselves. This can be seen in the different results of Donald (1958) who concluded there was interaction between nutrients and light and of King (1971) and Snaydon (1971) who concluded that there was no such interaction. Hall (1974a) has drawn attention to the complexity of the problem as revealed by the very different views of certain investigators. For example, when de Wit (1960) speaks of competition for space between species, space being interpreted as a composite of growth factors and resources such as water, nutrients, light etc., he suggests that it is neither advisable nor necessary to subdivide the component of growth in studying the competition. This argument has been strongly debated by Donald (1963) who suggested that the use of space for all growth factors may be a convenient short hand for mass competition. Donald emphasized that it could be worthwhile to determine the real factor for which competition is occurring rather than just ignore it. Aspinall and Milthorpe (1959), see also Aspinall (1961) and Hall (1974a, b) demonstrated that specific partitioning of growth factors increased our understanding of the growth process between plants in association and how they should be managed.

Harper (1961) emphasized that in examing analyses of plant competition it is important to distinguish between those carried out by agronomists, ecologists and geneticists, as their concepts and objectives are very different. As has been emphasized in Section II.3, this study is concerned with competition analysis in the context of intercropping systems, i.e. competition from the agronomist's point of view. In studying competition, agronomists are concerned with the ways in which the resources of an environment may best be used in crop production (Harper, 1961). As one of our objectives in conducting intercropping experiments is to get the maximal yield of each crop or the maximum combined yield, our competition studies should relate to those final yields. In most intercropping studies, however, the better use of resources is simply assumed because of higher yield (Trenbath, 1978, Natarajan and Willey, 1979, Willey, 1979, Willey and Rao, 1980). As has been emphasized by Aspinall and Milthorpe (1959) and others, it is important for a better understanding to know of what the major competition usually consists in mixed cropping and how resources are used by crops. This may help to explain how the final yield is developed and may be useful for further improvement of mixed croppping by managing the growth factors during the growth of crops.

The purpose of this study is to demonstrate how we should examine the competition analysis for intercropping systems in order to aid our understanding of final yield. The study involves the comparison of the previous competition models that are widely used in intercropping studies and our proposed competition analysis for intercropping systems.

2. THE COMPARISON OF THE PREVIOUS COMPETITION MODELS

The competition function which is popular in ecological studies and has been tried for intercropping systems (Willey, 1979) is the Relative Crowding Coefficient of de Wit (1960). As it was designed for mixtures in a replacement series, it cannot be applied to the additive situation as in intercropping systems (Willey and Rao, 1980, Spitter, 1983). Sakai (1961) and Spitter (1983a, b) proposed another method to examine competition in intercropping, especially for examining the effects of spacing and density. The method basically is regression of yield on a range of spacings or densities. The other methods that are designed to describe competition in intercropping, including the Relative Crowding Coefficient, have been reviewed in detail in Section II.3. I noted in Section II.4 that all these concepts have their own limitations.

From Section III.2 and Section IV.2, experimenters tend to be interested in comparing between intercrop treatments rather than between sole crops and intercrops. As a result the availability of sole crop treatments in each experiment is also limited. To calculate the competition Index requires a sufficient range of densities in sole crop treatments to enable a density-yield curve to be fitted (Donald, 1963). Therefore, this function is not widely used for intercropping systems (Willey, 1979) and it will not be included in this study. The regression methods of Sakai (1961) and Spitter (1983a, b) are also not included since they are only for spacing treatments or density treatments. The three competition functions (Willey, 1979) and the Competitive Ratio of Willey and Rao (1980) will be compared by using both experimental data and some theory.

The results of analysis of those four competition functions for some experiments on intercropped maize and soybean or maize and mungbean appear in Table 6.1.a and 6.1.b. The five experiments are mainly intercropping combinations of maize genotypes and soybean genotypes (Table 6.1.a) and of maize genotypes and mungbean genotypes (Table 6.1.b). These experiments are representative of Indonesian intercropping systems and all have 0.50: 0.50 intercrops (i.e. the density of crop in pure culture is equal to in intercrops).

From Tables 6.1.a and 6.1.b, it appears in general that the indications of dominance or aggressiveness of the two crops in each combination with experiments that are detected by Relative Crowding Coefficient, Aggressivity, the component LER_s and the Competitive Ratio are in fact consistent. The reason for this will be discussed later. Inspection of the four competition functions of maize (i.e. k_m, A_m, L_{cm} and CR_m) suggests that in general maize is more aggresive or competitive than either soybean (Table 6.1.a) or mungbean (Table 6.1.b). As well as detecting more or less competition, the Relative Crowding Coefficient is also designed to show when the mixed crop yields more than expected which is when $k_s > 1.00$. This can also be seen in the component LER_s (L_C) where $L_{Cs} \geqslant 0.50$ (as $k_s = 1.0$ is equivalent to $L_{Cs} = 0.50$). Variation of the two competition functions (k_s and L_{Cs}) across treatments and experiments suggests that most of the component crop yields are more than expected and even higher than sole crop yields, as indicated by the negative values of k_s or $L_{Cs} > 1.00$. The Aggressivity and Competive Ratio are not designed to solve this problem.

Willey and Rao (1980) showed that Aggressivity and Competitive Ratio are in fact functions of the component LERs. We will show that the Relative Crowding Coefficient is also a function of the component LERs.

Let us rewrite the Relative Crowding Coefficient for 0.50: 0.50 mixtures from (2.31) as

$$k_{ab} = \frac{MA}{SA - MA} \quad \text{and} \quad k_{ba} = \frac{MB}{SB - MB}$$

then

$$k_{ab} = \frac{MA}{SA}\left(\frac{1}{1 - \frac{MA}{SA}}\right)$$

or

$$k_{ab} = \frac{L_{CA}}{1 - L_{CA}} \tag{6.1}$$

and

$$k_{ba} = \frac{L_{CB}}{1 - L_{CB}} \quad (6.2)$$

where MA and MB are the yield of crop A and B in mixture and SA and SB are the yield of crop A and B in sole crop respectively. L_{CA} and L_{CB} are the component LERs of crop A and crop B respectively.

From this result it appears that the three competition functions, (i.e. Relative Crowding Coefficient, Aggressivity and Competitive Ratio) are all functions of the component LERs, which accounts for the similarity over treatments of the variation in competition functions.

Willey (1979) emphasized that in the additive situation found in most intercropping systems, the required optimum population may be higher in intercropping than sole cropping at least for some combinations. From Tables 6.1.a and 6.1.b, there are several combinations either maize and soybean or of maize and mungbean with the component crop yields higher in intercrop than in sole crop. This shows that the Relative Crowding Coefficient is not identifying competition between crop in intercropping systems. This is because each crop's coefficient indicates the degree of competition relative to sole cropping for mixtures of replacement series (Rao and Willey, 1980, Spitter, 1983a, b).

In proposing the Competitive Ratio, Willey and Rao (1980) argue that Relative Crowding Coefficient and Aggressivity values cannot give a quantitative measure of competitive ability between two crops and can only indicate that a given crop is more or less competitive to the other crop. Furthermore, they argued that the same Aggressivity values for mixed crops (see Section II.4) can give different degrees of yield advantages. Therefore it is difficult to argue that the competitive ability of the first crop relative to the second crop is constant across the systems as they have different degrees of yield advantages. Before we leave the Relative Crowding Coefficient and discuss in more detail

Aggressivity and Competitive Ratio it is important to restate that the Relative Crowding Coefficient is designed to measure the degree of competitive ability of two crops of different species (de Wit, 1960, Bakhuis and Kleter, 1965, van den Bergh, 1968, Hall, 1974a, b) and is not proposed to measure the yield advantages in mixed crops as argued by Mead and Riley (1981) though the product of k_s can indicate the degree of yield advantage as van den Bergh (1968) emphasized that in the extreme the product of k_s is related to the Relative Yield Total or LERs.

As the Competitive Ratio is also a function of the component LERs and is only the ratio of the component LERs, then the argument of a constant competitive ability of the first crop to the second crop but having different combined relative yield or LER is also applied for this coefficient. Consider an example of additive intercropping systems of 0.50: 0.50 mixtures that would give the component LERs of 0.50: 0.25; 0.60: 0.30; 0.70: 0.35; 0.80: 0.40; 0.90: 0.45; etc. These would all give the same competitive ability of the first crop, i.e. twice that of the second crop, but having different degrees of yield advantages. Again this result indicates that by use the CR values it will also be difficult to argue that the competitive abilities of the two crops are constant across systems. It appears that As and CRs are in fact equivalent, where As is based on the difference of the component LERs while CRs is based on the ratio of the component LERs.

In order to examine further the relation of As to CRs, we will consider the bivariate graphical method (see Section II.1). The assumptions of the method have been examined in Section IV.1.2 and its usefulness has been demonstrated in Section IV.2 and Chapter V. In Section IV.2, I elaborated the method by constructing the line of equal or constant LER values and in this Chapter I construct another set of lines that show a constant line of Competitive Ratio and Aggressivity values.

Suppose, first, that the slope of the first crop yield (X_1) regressed on the second crop yield (X_2) is one (i.e. the line of $\delta = 45°$ in terms of X_1 and X_2 axes). It appears from the results in Section IV.2 that the crops in intercropping systems are not really independent so that the transformation of X_1 and X_2 to Y_1 and Y_2 or Z_1 and Z_2 as in bivariate analysis (Pearce and Gilliver, 1978, 1979, Gilliver and Pearce, 1983) is to be preferred.

From formulae 2.1.9 and 2.1.10 we have

$$X_1 = Y_1 \sqrt{V_{11}} \qquad \text{and} \qquad X_2 = Y_2 \sqrt{V'_{22}} + Y_1 \frac{V_{12}}{\sqrt{V_{11}}} .$$

When $X_1 = X_2$,

$$\frac{(V_{11} - V_{12}).\ Y_1}{\sqrt{V_{11}}} - \sqrt{V'_{22}}.Y_2 = 0 .$$

This is the equation through the origin of slope δ where

$$\tan \delta = \frac{(V_{11} - V_{12})}{\sqrt{V'_{22}V_{11}}} . \qquad (6.3)$$

All the points on this line (i.e. $Y_1 = Y_2\sqrt{V_{11}V'_{22}} / (V_{11} - V_{22})$) have the yield of the first crop the same as the yield of the second crop, but having different combined yields.

If it is desired to construct the equation of the case of where the yield of the first crop is λ times of the second (i.e. $\frac{X_1}{X_2} = \lambda$) the formula of 6.3 is easily modified as

$$\tan \delta = \frac{(V_{11} - V_{12})}{\lambda \sqrt{V'_{22}V_{11}}} \qquad (6.4)$$

As there could be a big difference in actual yield of the two crops, working on the relative yield (i.e. on the component LERs) would be preferred. By substituting S_1/S_2 for λ in formula 6.4 where S_1 and S_2

are the yield of the first and second crop respectively, we can construct the line having the same proportion of the component LERs of the two crops in the intercropping system. This line is the line of constant CRs = 1.0 or As = 0.0. The other lines through the origin at different δ indicate the constant CRs at different ratios of the component LERs. Lines of constant Aggressivity values other than As = 0.0 can easily be drawn as the set of lines parallel to the line of As = 0.0. Then all results are plotted in terms of bivariate display as appear in Fig 6.1 by assuming that the correlation of the two crop yields is positive for all treatments (see Section II.1).

Again from Fig. 6.1 it appears that the degree of competitive ability detected by either CRs or As is in fact equivalent. For the points that lie on the right hand side of the line CRs = 1.0 or As = 0.0, the first crop is more competitive, i.e. CRs $\geqslant$ 1.0 or As $\geqslant$ 0.0. On the other hand for points that lie on the left hand side of the line CRs = 1.0 or As = 0.0, the first crop is less competitive than the second crop, i.e. CRs $\leqslant$ 1.0 or As $\leqslant$ 0.0. In fact, the line CRs = 1.0 or As = 0.0 is also the line of equal value of the Relative Crowding Coefficient of the two crops (i.e. $k_{ab} = k_{ba}$). This fact is easily seen in the formula (6.1) and (6.2). If it is true that the component LERs of the two crops are euqal (i.e. $L_{CA} = L_{CB}$), then substitution of L_{CB} by L_{CB} in 6.1 or L_{CB} by L_{CA} in 6.2 will show that $k_{ab} = k_{ba}$. Other lines of constant difference between k_s (i.e. $k_{ab} - k_{ba} = \lambda$) are not as simple as the lines of constant CRs or As, i.e. they are not straight lines. The relation of the two component LERs (i.e. L_{CA} and L_{CB}) in the Relative Crowding Coefficient is not linear but is of the form of a rectangular hyperbola,

i.e.

$$L_{CA} = \frac{(1 + \lambda)L_{CB} - \lambda}{L_{CB} + 1 - \lambda} \tag{6.3}$$

Thus, it appears that the constant values of CRs or As or k_s can occur at different levels of yield advantages as indicated by the line of equal LERs. Hence it would be dificult to argue that the competition of the two crops along the line of the same λ is constant for all systems as they have different degrees of yield advantage. The other situation also shows the relative inutility of the three competition functions in detecting the degree of competetion between two crops. Consider an example of the two intercrop systems (i.e. intercrop 1 and 2 in Fig. 6.1). In intercrop 1 the first crop is more competitive than the second crop, while in intercrop 2 the first crop is less competitive.

Hence, merely considering the functions themselves has limited value and adds little to our knowledge in respect of the final yield. As our goal in intercropping is to get the highest yields on combined yield, the distinction between yield advantage (i.e. LER $<$ 1.0) or disadvantage (i.e. LER $>$ 1.0) is clearly important. This has also been emphasized by de Wit (1960) and Hall (1974a, b) as non-competitive ($k \geqslant 1.0$) or competitive ($k \leqslant 1.0$) interference, though k_s themselves are already inadequate due to the yield in the mixture being larger than pure culture. The usefulness of this distinction, however, has been ignored in considering only the competition functions (see Trenbath, 1978, Willey and Rao, 1980, Faris et al., 1983). I have already emphasized that the objective in analysing competition for intercroppings is to assess final yield. Therefore, consider the yield advantages and secondly whether a crop is dominant or dominated. The criterion of yield dominant is important if it is desired that as well as LER values the proportion of the main crop should also be considered (see the concept of the new effective LER). Hence, the degrees of dominance of the two crops could be the same, but the meaning probably would be different. For example in the situation of no yield advantage (i.e. LER $<$ 1.0), the two crops may compete for the same resource or resources, while in the situation of yield advantage (i.e. LER > 1.0), compensation or cooperation between two crops may take place rather than competition (Harper, 1961).

As a result of this the next section will discuss the usefulness of bivariate analysis in examining the final yield of intercropping systems together with the additional growth analysis of the two crops involved in intercropping systems.

3. PROPOSED ANALYSIS IN EXAMINING COMPETITION FOR INTERCROPPING SYSTEMS

It appears from the previous section that without considering the degree of yield advantage in intercropping systems, the competition functions (i.e. k_s, A_s and CR_s) that are already proposed are relatively ineffective and even the Relative Crowding Coefficient cannot always detect competitive ability as the yields of some crops in intercrops are higher than sole crop yield. Therefore the method should be directed to examine the main goal of intercropping experiments, i.e. the highest yield of crops or the combined yield of those crops.

Before we discuss some experiments in more detail in order to examine final yield by considering not only the yield itself but also the growth character and the yield components of crops, the bivariate method will be applied to the two experiments (i.e. experiment 8 and 9) already analysed (Table 6.1).

Results for these two experiments are plotted in Figs. 6.2 and 6.3. Inspection of these figures and comparison with Table 6.1 reveals that in general maize is more aggressive than either mungbean or soybean. The association of the two crops (maize and mungbean or maize and soybean) in most cases is cooperative or at least compensatory (i.e. LERs ⩾ 1.0). From Fig. 6.2, considering only the degree of dominance, we can assess the argument of the previous section. Consider treatment 3 in that figure: maize appears to be more aggressive than mungbean but there is lower maize yield than treatment 5 in which maize is less aggressive.

The converse result is seen in treatments a and f (Fig. 6.3), these two treatments having the same degree of dominance of the first crop over the second crop, but having different degrees of yield advantage. These two figures provide practical problems in using competition functions without considering yield advantages.

Hence our claim that in order to examine the final yield of crops for intercropping systems it is not enough to consider only the yields themselves; one should also include the other factors of crops which influence yield. The bivariate method itself provides useful results, not only the degree of yield advantage but also the degree of dominance between the two crops. To reiterate, our goal now is to examine how the final yields of the two crops as displayed by bivariate method are better understood by considering the other characters of crops.

The three experiments of maize and peanut intercropped will be discussed in detail by considering growth data and yield components.

The first experiment was designed to examine the effect of weeding methods (experiment 16). The result of bivariate analysis was highly significant (Table 4.2.21 in Section IV.2) and is displayed in Fig. 6.4 From this figure it appears that the effect of weeding methods is mainly on maize yield. It appears that the maize is not strong enough to compete with weeds since maize yield is depressed in unweeded treatment (W_0). Weeding either by hand (W_1) or by hock-hoe (W_2) or by herbicide (W_3) increases the yield of maize and for W_3 this is even more than twice that of W_0. The other result from Fig. 6.4 is that the competition occurs (i.e. LER $\leqslant$ 1.0) on treatment W_0, but compensation or cooperation takes place on the other treatments. Examining the line of equal yield of peanut and maize one sees that the maize is more aggressive than peanut when the field is weeded, while peanut is more aggressive for the unweeded system. However, in terms of the relative yield (i.e. the component LERs) of all treatments it appears that peanut is more aggressive (or that the yield proportion of peanut is more than maize). This result also indicates that the yield of peanut is not as much reduced as maize in intercropping systems.

This result clearly shows that the final yields are affected by weeding treatments. Hence, we aim to examine the growth of the two crops as influenced by weeding treatments. The growth of a crop is usually well represented by taking the yield of dry matter as an integrative measure of the combined effects of photosynthesis and respiration during the growth season (Donal and Hamblin, 1976, Baker and Gebeyehou, 1982). By regarding time of observations as a factor and transforming the data (i.e. yield of dry matter and Leaf Area Index (LAI)) into $\ln(X + 1)$, we can analyse the growth of maize and peanut. The results of analyses of variance of these two growth characters of maize and peanut appear in Table 6.2 and 6.3. As well as significant treatment effects there are also significant interactions between treatment and time of observation. Hence, it is likely that the growth curves of maize underlying the yield of dry matter and Leaf Area Index are in fact different during the growth season. However, neither weeding nor its interactions with time is significant for either yield of dry matter or LAI of peanut. This result indicates that the growth of peanut is not affected in association with maize by weeding. The development of dry matter of maize and peanut during the growth season is clearly shown in Fig. 6.5 and 6.6. From Fig. 6.5 it appears that until 45 days after planting the growth rate of maize is still similar (i.e. the curves may be taken to be approximately parallel), but later the growth of unweeded maize is depressed. The growth of peanut, again, shows remarkable constancy of pattern over the four treatments from the beginning of planting till harvest time (Fig. 6.6), in agreement with the results in Tables 6.2 and 6.3. Returning to Fig. 6.5, one sees that weeding affects the growth of maize after 45 days of planting. This could also indicate that weeding before 30 days after planting may not be necessary as the growth of maize till 30 days old is not significantly different, but the divergence is consistent with an effect of not weeding throughout, so that the agronomic recommendation from this experiment alone would be to use weeding.

The effect of weeding on maize and peanut can also be seen from the association of crop yield on weight of dry weed as influenced by treatments and crop characters. The regression of yield of maize and peanut on weed dry weight is shown in Fig. 6.7. It appears that increasing the dry weight of weed highly significantly reduces the yield of maize (i.e. t = 25.84**), while the relative yield of peanut is not significantly reduced (i.e. t = 1.92). The correlation matrices for weight of dry weed and other characters of maize and peanut are presented in Tables 6.4 and 6.5. The weight of dry weed is highly negatively correlated with the growth characters and component yield of maize in most cases (Table 6.4). Hence, the presence of weed depresses the growth of maize and reduces its final yield. This result can also be seen on the correlation pattern for yield of maize which shows significant positive correlation with the other characters and also positive correlations between those characters (Table 6.4). On the other hand, though the peanut growth characters and yield components and grain yield are correlated with each other they are not significantly affected by the presence of weed. (Multiple regression of crop yield on weed weight and yield components might be unsatisfactory given the high intercorrelation among these X-variables) (Table 6.5).

From all these results it appears that the reduction in grain yield of maize due to the presence of weed results from depression of all yield components during growth and development. Peanut, on the other hand, with its very different growth habit, was much less affected by weeds.

The approach of experiment 16 is applied to experiment 17. This experimental intercropping of maize and peanut was designed to examine the effect of date of planting of maize and peanut (see Section III.2). The result of bivariate analysis is in Fig. 6.8. It appears that all treatments show yield advantages (i.e. LER $\geqslant$ 1.00) so that compensation or cooperation may occur for these two crops. The line of equal yield proportion is such that in all cases maize is dominant. The earliest time of maize planting before growing peanut gives higher yield for both maize and peanut while the earlier planting of peanut before growing maize depresses the yield of maize. The responses of maize and peanut are clearly shown by regressing the yields of those two crops on planting date of maize (Fig. 6.9). It appears that maize yield is linearly dependent on planting date while peanut yield is quadratically dependent on the planting date. It also appears that delaying maize planting reduces maize yield while yield of peanut is also depressed, but at a certain time (i.e. where maize is planted after peanut) the yield of peanut increases again. This result shows the importance of partial differences in the time of utilization of resources for growth (Snaydon and Haris, 1979). Maize and peanut planted at the same time gives an intermediate yield of peanut and maize compared with the other two treatments (i.e. peanut planted 14 days earlier which gives higher yield of peanut but lower yield of maize and in contrast when maize is grown 14 days earlier than peanut) (see treatments +14, 0 and -14 in Fig. 6.8). As the 55 days and 69 days earlier of growing of maize before growing peanut would only give 35 days and 16 days growth overlap respectively between maize and peanut then those two combinations give the least growth interference with each other and hence the highest yields. This may not be always true as Donald (1963) and Snaydon and Haris (1979) emphasized that two crops can grow better without influencing each other if the requirements of the two crops are independent or a different time of requirement.

Growth characters of maize and peanut clearly influence the final yield result, as of course is expected (Tables 6.6 and 6.7). The growth characters of maize (i.e. yield of dry matter, leaf area index, number of leaves) show the differences of rate of growth of maize between treatments as manifest in interaction of treatments and time of observation (Table 6.6). On the other hand, though in general the rate of growth of peanut (i.e. yield of dry matter, leaf area index and number of leaf) is not significantly different, since initial growth differs between treatments, the total growth of peanut is also different (Table 6.7). This can also be seen in the development of yield of dry matter of maize and peanut (Figs. 6.10 and 6.11). The different accumulation of dry matter of maize over treatments is clear (Fig. 6.10). The growth of maize planted 55 days and 69 days earlier than peanut is not significantly different till 75 days after planting since these two treatments are not affected by peanut till 55 days and 69 days respectively. This result shows that growing peanut even 30 days before harvesting (i.e. treatment -55) is still giving different responses from both maize and peanut (Fig. 6.10). The growth of peanut, however, as appears in Fig. 6.11, shows approximately parallel curves between the treatments which indicates similar rates of growth but different total growth (Table 6.7).

The effect of date of planting on yield components or growth characters of peanut and maize at harvest time can be seen from the correlation matrices for those variables (Tables 6.8 and 6.9). From Table 6.8 it appears that yield of dry matter at harvest time and yield components are negatively correlated with the treatments. That is, delaying the date of planting of maize intercropped with peanut reduces the yield of dry matter and yield components of maize. As a result the grain yield is also depressed as the growth and yield component of maize are of course highly positively correlated with the grain yield (Table 6.8). Peanut characters show the same pattern (Table 6.9). Both dry matter production and number of branches and weight of 1000 seed are negatively correlated with the treatments and of course yield components are positively correlated with yield (Table 6.9). Again all these results demonstrate how the growth of crops is influenced by the treatments and consequently these growth characters determine the final yield.

The bivariate analysis was also applied to experiment 7 which examined the effect of nitrogen fertilizer on intercropped maize and peanut (Fig. 6.12). It appears that four treatments are clearly distinguishable from each other. Increasing nitrogen fertilizer results in an increased yield of maize but a decreased yield of peanut. It appears that at higher levels of nitrogen peanut yield is depressed by the improved performance of the maize. The line of equal LER in the figure also suggests that cooperation or compensation (i.e. LER $\geqslant$ 1.0) occurred except at low nitrogen (i.e. N_0). At a low level of nitrogen the peanut is dominant as it can fix N_2 from the air, but as the nitrogen fertilizer increases the maize grows very rapidly and depresses the growth of peanut. It seems that strong growth of maize requires more resources such as light, nutrients except nitrogen etc., and these factors may be limiting for peanut so that the growth of peanut is depressed. This can also be seen in the results of bivariate analysis on nitrogen uptake of maize and peanut (Fig. 6.13). It appears that nitrogen uptake equivalence ratio total (i.e. calculated as NUER*)) of all treatments is greater than 1.0 even for N_0 . Hence, the efficiency of nitrogen uptake is greater in intercropping than sole cropping, a very worthwile finding if generally true in these environments. At low nitrogen level, the compensation of

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*) $$\text{NUER} = \frac{\text{N. uptake of maize intercrop}}{\text{N. uptake of maize sole crop}} + \frac{\text{N. uptake of peanut intercrop}}{\text{N. uptake of peanut sole crop}}$$

nitrogen uptake from peanut makes the total nitrogen uptake equivalence ratio exceed unity. It could be said that even at low nitrogen the compensation of nitrogen uptake takes place rather than competition between those two crops (Hall, 1974a, b), though the fact is that nitrogen limits the growth of maize at low level of soil nitrogen (Wagner, 1954). The capability of peanut to fix N_2 from the air makes the balance of the total nitrogen uptake equivalance ratio so that increasing doses of nitrogen do not increase the total uptake nitrogen equivalence ratio (i.e. the four treatments almost lie on the same line of equal NUER* (Fig. 6.13). This indicates that as nitrogen availability in the soil increases peanut tends to use nitrogen from the soil and reduces fixation from the air (Miller et al, 1982). From Fig. 6.13 it also appears that at low nitrogen fertilizer (i.e. until N 45kg/ha) nitrogen uptake by peanut is dominant while at higher levels uptake by maize is dominant. Returning to Fig. 6.12, and comparing it with Fig. 6.13, we see that at N 90kg/ha though the nitrogen uptake by maize is dominant the yield proportion of maize is less than that of peanut. This result may indicate that the requirement of nitrogen is greater for maize in order to produce the higher yield of maize. It also appears that the higher performance of maize due to increased nitrogen, fertilizer needs more of other nutrients, light, etc., and these growth factors become limiting for maize and peanut. On the other hand, at a low level of nitrogen fertilizer, peanut can fix nitrogen and it may also need more of the other nutrients and these may become limiting for maize.

I emphasized earlier that our understanding of the final yield response would be improved by examining attributes other than yield such as growth characters. The analysis of variance of ln (dry matter + 1) and ln (LAI + 1) of maize and peanut were done during the growth time

(Tables 6.10 and 6.11). From Table 6.10 it appears that both treatment effects and interaction of treatments and time of observation of yield and of dry matter of maize and peanut are significant. This indicates that not only are the total yields of dry matter of the two crops different between treatments but also the rates of development of these yields of dry matter are different. The result of the analysis of leaf area index (Table 6.11) is consistent with that for dry matter. The leaf area index of both maize and peanut is significantly influenced by growth time.

Plotting yield of dry matter against time of observation as in Figs. 6.14 and 6.15 clarifies the results in Table 6.10. From Fig. 6.14, it appears that the rate of growth of yield of dry matter of maize is depressed at low nitrogen levels, while at high nitrogen level the process of dry matter accumulation continues till the harvest time. On the other hand, initial growth of dry matter of peanut (Fig. 6.15) does not vary significantly with nitrogen level, but as the maize grows very rapidly it shades the peanut (i.e. for the high level of nitrogen) and consequently depresses the growth of peanut. At low nitrogen, however, initial growth is probably rather slow through the low nitrogen availability in the soil, followed by satisfactory growth as a result of nitrogen fixation from the air.

The result of bivariate analysis on grain yield of maize and peanut (Fig. 6.12) indicates that increasing nitrogen fertilizer is followed by an increase in yield of maize but a decrease in yield of peanut. This could also be examined in more detail by regressing the dry matter yield of the two crops on the doses of nitrogen fertilizer (Fig. 6.16). It appears that the effect of nitrogen fertilizer is positively linearly significant ($t = 15.49^{**}$) to the maize yield, while to the peanut yield it is negatively linear ($t = 6.47^{**}$) with increasing doses of nitrogen fertilizer. This result indicates that maize is more responsive to the nitrogen fertilizer.

The influence of nitrogen fertilizer on the other attributes of maize and peanut can be seen in Table 6.12 and 6.13. Increasing nitrogen fertilizer is followed by increased nitrogen uptake, yield of dry matter, and other yield components of maize as indicated by positive r values between these attributes (Table 6.12). It also appears that nitrogen uptake, yield of dry matter and yield components determine the grain yield of maize, as of course is to be expected. On the other hand, the reduction in peanut yield due to the increase of nitrogen fertilizer appears via the reduction of nitrogen uptake, yield of dry matter and number of branches of peanut (Table 6.13).

These experiments suggest which components of maize yield and peanut yield are affected by the treatments and what factors appear to be limiting growth under certain conditions. A better understanding of influences on plant growth is necessary for the future development of intercropping systems.

4. DISCUSSION AND SUMMARY

Clement et al. (1929), when pioneering competition studies, emphasized that botanical properties of crops such as tallness and large leaves are important components for measuring competitive ability of crops in mixture. However, the results of Sakai and Gotoh (1960), Oka (1960), Jenning and de Jesus (1968) and others did not support Clement et al. The results of Sakai and others appear to be that the yields of crops in mixture are not correlated with high competitive ability of crops in mixture. Even the potential yield of a crop itself in pure culture is not always a useful criterion for measuring the competitive ability of crops in mixture (see Chapter V). The result of Chapter V shows that the highest yield of a genotype in pure culture is not always the highest one in the mixture as well. The performance of a crop in the mxiture is greatly affected by its crop combination and environments as well. Sakai (1961) and Donald (1963) also emphasized that although the competitive ability of a crop may have a genetic basis, there can also be an effect on competition for environmental components, such as light, water, nutrients, etc.

In studying crop interference, it would seem advantageous to distinguish between competition, neutrality and cooperation (Harper, 1961, Hall, 1974a, b). It was suggested by Mead (1968) that the correlation between the yield of a crop and the yield of its neighbour can be used to measure the degree of competition. This idea encompasses the correlations of the two crops' yields within the treatment in each experiment which has already been presented in Section IV.1.2. The results of Section IV.1.2 may identify which treatments or combinations show competition or cooperation. From Section IV.1.2, the association of two crops that involve fertilizer and density treatments may vary from competition to cooperation. At low levels of fertilizer competition may occur, but as fertilizer increases the association may vary to neutrality or cooperation or in contrast as in experiment 7 as discussed in the previous section. At high levels of nitrogen, the availability of nitrogen in the soil for the two crops could be more than enough, but as a consequence of growing well, both crops require more of other nutrients or light, these factors becoming limiting for both crops. By this correlation technique, we can improve our understanding of the degree of association of the two crops in mixture. However, our goal in conducting intercropping experiments is not to get the highest degree of neutralism or cooperation between the two crops but rather to get the highest yields or combined yield of the two crops. The highest positive correlation of the two crop yields with a given treatment may not be desired as the yields or combined yield of those two crops are not the highest as well. Consider the results of experiment 1 presented in Fig. 6.17. Examining Fig. 6.17, together with Table 6.14, (reproduced from Table 4.1.2.6), one sees that the highest LER is not found with the highest degree of cooperation between maize and peanut in that system and even has a non-significant negative association between the two yields. Of course, in accepting the LER as the criterion of yield advantage, one should still use it very cautiously, as the LER takes into account the larger yields of both crops simultaneously. However, by having as the other criterion the proportion of peanut requirement to be at least 40% of sole crop, the intercrop 4 would be preferred (see the concept of the new effective LER in Chapter IV.2). It also appears that considering the degree of association between the two crop yields itself does not add anything if the yield advantages are ignored.

It is also clear from the previous sections that without distinguishing the degree of yield advantage the previous competition functions are largely uninformative for intercroppings. Even the Relative Crowding Coefficient developed with the criterion of competitive or non-competitive interference is of little use as the additive situation is the most common one rather than the replacement series (Willey, 1979, Willey and Rao, 1980). This study shows that it is quite common to get crop yields in mixtures higher than in sole crops even with the maximum sole crop standardisation. The Aggressivity and the Competitive Ratio coefficient are equivalent but the latter gives the absolute value of the degree of dominance of the first crop relative to the second crop or vice-versa. As a result of this, Willey and Rao (1980) emphasized the usefulness of this coefficient and also advocated seeking the maximum LER by correlating the CRs and LERs. This method has been applied by Faris et al., (1983), who concluded that CRs and LERs are independent. This result can be understood by examining the bivariate graphical method (Fig. 6.1). I have already discussed how the values of CR can be equal at different values of LER and if so then the CRs and LERs may be independent. This result shows how the little value may lie in relating the values of CR and LER. I have emphasized that the LERs should be used very cautiously. Even with the highest CRs of the first crop to the second crop in a given treatment, there may not be the highest yield of the first crop as well (see intercrops 1 and 2 in Fig. 6.1). This fact has also been discussed in Chapter IV.2, i.e. that the highest value of the ratio is a property of a particular numerator and a particular denominator. As a result the value of CR are not comparable between intercropping treatments in a given experiment. Again this result indicates the importance of distinguishing the degree of absolute yield advantage in intercropping experiments. Competition studies in intercropping experiments should be directed towards an understanding of the determination of the final yields.

The importance of growth and the other characters of crops in determining the final yield has long been recognised by agronomists (Evan, 1971, Donald and Hamblin, 1976, Baker and Gebeyohou, 1982). These attributes have also been used extensively in examining competition between crops in mixtures (Aspinall and Milthorpe, 1959, Aspinall, 1960, Sakai, 1961, Donald, 1963). Most of the workers cited have also emphasized that competition is a result of environmental factors such as light, water, nutrients, etc. This approach, however, has been somewhat neglected (Hall, 1974a, b) much work being simply concerned with the yields of the two crops themselves (de Wit, 1961, McGilchrist and Trenbath, 1965, Trenbath, 1978, Willey, 1979, Willey and Rao, 1980). The analysis of crop traits other than yields in the three maize and peanut intercropping experiments clearly demonstrates how competition occurs through treatment effects such as time of sowing and also shows which variables are influential in the overall change in final yield.

The final yields or combined yields in intercropping are the most important criteria, but examining the yields themselves usually does not add anything to our knowledge of how these final yields arose and could best be achieved. Again the bivariate graphical method for two crop yields provides not only the two crop yields as a response to treatments and the degree of yield advantage in terms of LER (see Section IV.2) but also can be used to identify the degree of yield dominance between the two crops at a given level of yield advantage. The method is useful not only in detecting the degree of dominance of the two crops but can also determine the other traits that are likely to be important in determining competition between two crops, whether nutrients uptake, light interception or whatever. Like the other methods, the bivariate analysis sometimes may fail, but its usefulness together with that of the new effective LER have been demonstrated in Section IV.2 in examining yield advantages and with regression techniques in Chapter V in examining yield stability among intercropping systems. The faulty assumption of equal correlation of crop yields for all treatments in bivariate analysis is still better than assuming that two crop yields are independent (Gilliver in the discussion of Mead and Stern, 1979; and see the result of Section IV.2 as well). Hence using the bivariate analysis and taking the investigation further through growth analysis or assessment of the other characteristics of crops provide a comprehensive analysis and would add a better understanding of how the final yield is determined. This knowledge will be useful for the future development of intercropping systems. Again, as in the previous chapter, our study of intercropping experiments should be directed towards examining the competition between intercropping systems and not between the sole crop and the intercrop. The presence of sole crop treatments under optimum conditions would provide a precise standardisation method in most intercropping systems.

Table 6.1.a Relative Crowding Coefficient (k_s), Aggressivity (A_s), the Component of LER (L_{Cs}) and the Competitive Ratio (CR_s) for maize and soybean intercropped.

	Experiment 9				Experiment 12								
						Maize 1				Maize 2			
TREATMENT	k_m k_s K	A_m A_s	L_{Cm} L_{Cs} LER	CR_m	TREATMENT SOYBEAN GENOTYPES	k_m k_s K	A_m A_s	L_{Cm} L_{Cs} LER	CR_m	k_m k_s K	A_m A_s	L_{Cm} L_{Cs} LER	CRm
1	> +) 3.098 >	0.756 -0.756	1.134 0.756	1.500	1	5.329 0.942 5.019	0.714 -0.714	0.842 0.485	1.736	> 0.479 >	1.676 -1.676	1.096 0.324	3.383
2	> 1.899 >	0.948 -0.948	1.129 0.655	1.724	2	8.434 1.674 14.117	0.536 -0.536	0.894 0.626	1.428	3.202 1.364 4.367	3.70 -3.70	0.762 0.577	1.321
3	> 1.597 >	1.514 -1.514	1.372 0.615	2.231	3	6.752 1.045 7.056	0.720 -0.720	0.871 0.511	1.705	4.780 0.618 2.955	0.890 -0.890	0.827 0.382	2.165
4	> 1.551 >	1.196 -1.196	1.206 0.608	1.984	4	5.757 0.695 4.000	0.884 -0.884	0.852 0.410	2.078	6.353 0.783 4.971	0.850 -0.850	0.864 0.439	1.968
5	124.000 > >	-0.132 0.132	0.992 1.058	0.938	5	> 0.927 >	1.076 -0.409	1.019 0.481	2.119	42.478 0.634 26.931	1.178 -1.178	0.977 0.388	2.518
6	> 4.208 >	0.804 -0.804	1.210 0.808	1.498	6	11.500 1.045 12.017	0.409 -0.409	0.920 0.511	1.800	3.425 1.179 4.037	0.466 -0.466	0.774 0.541	1.431
7	> 3.329 >	1.084 -1.084	1.311 0.769	1.705	7								

+) > = k or K is negative due to the intercrop yield > sole crop yield

TABLE 6.1.b Relative Crowding Coefficient (k_s), Aggressivity (A_s), the Component LER (L_{Cs}) and the Competitive Ratio (CR_s) for maize and mungbean intercropped.

TREATMENT MUNGBEAN GENOTYPES	EXPERIMENT 8				EXPERIMENT 13 Maize 1				EXPERIMENT 13 Maize 2				EXPERIMENT 14 Maize 1				EXPERIMENT 14 Maize 2			
	k_m	A_m	L_{Cm}	CR_m	k_m	A_m	L_{Cm}		k_m	A_m	L_{Cm}	CR_m	k_m	A_m	L_{Cm}	CRm	k_m	A_m	L_{Cm}	CR_m
	k_{mb}	A_{mb}	L_{Cmb}	CR	k_{mb}	A_{mb}	L_{Cmb}		k_{mb}	A_{mb}	L_{Cmb}		k_{mb}	A_{mb}	L_{Cmb}		k_{mb}	A_{mb}	L_{Cmb}	
	K		LER		K		LER		K		LER		K		LER		K		LER	
1	1.179	0.064	0.541	1.063	9.638	-0.504	0.906	0.782	10.494	-0.020	0.913	0.989	>	1.028	1.161	1.794	3.367	0.406	0.771	1.357
	1.037		0.509		>		1.158		11.987				1.833		0.647		1.315		0.568	
	1.022				>				125.795				>				4.427			
2	1.193	0.138	0.544	1.145	2.086	0.922	0.676	0.595	23.316	-0.034	0.962	0.983	>	1.228	1.180	2.085	5.250	0.686	0.840	1.690
	0.905		0.475		>		1.137		46.619		0.979		1.304		0.566		0.988		0.497	
	1.079				>				1180.198				>				5.187			
3	1.037	0.446	0.509	1.780	10.675	0.212	0.915	1.131	7.547	0.446	0.883	1.338	>	1.392	1.143	2.557	4.618	0.742	0.822	1.823
	0.401		0.286		4.236		0.809		1.941		0.660		0.808		0.447		0.821		0.451	
	0.415				45.595				14.650				>				3.794			
4	2.106	0.202	0.678	1.175	3.274	0.132	0.766	1.094	10.628	0.430	0.914	1.308	>	1.580	1.176	3.047	6.143	0.820	0.860	1.911
	1.364		0.577		2.333		0.700		2.322		0.699		0.629		0.386		0.818		0.450	
	2.872				7.638				24.681				>				5.026			
5	1.358	-0.078	0.576	0.937	4.000	-0.206	0.800	0.886	13.286	0.462	0.930	1.330	>	1.382	1.196	2.368	4.525	0.872	0.819	2.611
	1.597		0.615		9.309		0.903		2.322		0.699		1.020		0.505		0.621		0.383	
	2.170				37.237				30.853				>				2.809			
6	1.421	0.006	0.587	1.005	5.579	1.656	0.848	42.400	9.204	1.770	0.902	53.059	>	2.100	1.113	17.667	4.525	1.456	0.819	9.000
	1.404		0.584		0.020		0.020		0.017		0.017		0.067		0.063		0.100		0.091	
	1.995				0.114				0.159				>				0.453			
7	1.257	-0.318	0.557	0.778																
	2.521		0.716																	
	3.170																			

TABLE 6.2. The analysis of variance of the yield of dry matter of maize and peanut during the growth season of experiment 16.

Source of Variation	DF	Maize Mean Square	Peanut Mean Square
Block	2	0.1285	0.0062
Weeding methods	3	2.5048**	0.0054
Time	5	30.1939**	6.5345**
Weeding methods.Time	15	0.1974**	0.0027
Residual	46	0.0552	0.0076
Total	71		

TABLE 6.3 The analysis of variance of leaf area index of maize and peanut during the growth season of experiment 16.

Source of Variation	DF	Maize Mean Square	Peanut Mean Square
Block	2	0.0056	0.0017
Weeding methods	3	0.0497**	0.0035
Time	5	0.7048**	1.7673**
Weeding methods.Time	15	0.0073**	0.0042
Residual	46	0.0009	0.0049
Total	71		

TABLE 6.4 The correlation matrices (r) of weight of dry weed, growth characters, yield components and grain yield of maize of experiment 16.

	1	2	3	4	5	6
1. Weed weight/plot	1.000					
2. Cob weight/plant	-0.789	1.000				
3. Dry matter weight/plot	-0.770	0.921	1.000			
4. Seed number/plant	-0.694	0.776	0.783	1.000		
5. Weight of 1000 seed	-0.380	0.458	0.434	0.354	1.000	
6. Grain yield/plot	-0.896	0.844	0.916	0.851	0.403	1.000

TABLE 6.5 The correlation matrices (r) of weight of dry weed, growth characters, yield components and grain yield of peanut of experiment 16.

	1	2	3	4	5	6
1. Weed weight/plot	1.000					
2. Pod number/plant	-0.511	1.000				
3. Dry matter weight/plot	-0.486	0.759**	1.000			
4. Seed number/plant	-0.478	0.579*	0.623*	1.000		
5. Weight of 1000 seed	-0.329	0.413	0.633*	0.228	1.000	
6. Grain yield/plot	-0.518	0.615*	0.683*	0.591*	0.107	1.000

TABLE 6.6 The analysis of variance of the yield of dry matter, leaf area index and number of leaves of maize during the growth time of experiment 17.

Source of Variation	DF	Mean Square DM	LAI	NL+)
Block	3	0.0091	0.0214	0.0037
Date of planting of peanut	4	5.0841**	6.1140*	1.1080**
Time	4	20.5794**	3.3657**	0.2511**
Date of planting peanut.Time	16	0.1698**	0.1806**	0.0139**
Residual	72	0.0046	0.0108	0.0020
Total	96			

TABLE 6.7 The analysis of variance of the yield of dry matter, leaf area index, number of leaves and number of branches of peanut during the growth time of experiment 17.

Source of Variation	DF	Mean Square DM	LAI	NL	NB+)
Block	3	0.0127	0.0257	0.0078	0.0024
Date of peanut planting	4	0.4084**	1.2215**	0.3872**	0.3013**
Time	4	7.6044**	7.2568**	2.9419**	0.3665**
Date of peanut planting.Time	16	0.0044	0.0306	0.0220	0.0740**
Residual	72	0.3379	0.3864	0.1522	0.0089
Total	96				

+) DM = Weight of Dry Matter
LAI = Leaf Area Index
NL = Number of Leaves
NB = Number of Branches

TABLE 6.8 The correlation matrices (r) of date of planting of maize, growth characters, yield components and grain yield of maize of experiment 17.

Maize	1	2	3	4	5	6
1. Date of planting	1.000					
2. Yield of dry matter/plant	-0.980	1.000				
3. Weight of 1000 seeds	-0.416	0.530	1.000			
4. Weight of husk/plant	-0.764	0.725	0.248	1.000		
5. Weight of cob/plant	-0.974	0.969	0.409	0.772	1.000	
6. Grain yield of maize	-0.946	0.944	0.515	0.678	0.946	1.000

TABLE 6.9 The correlation matrices (r) of date of planting of maize, growth characters, weight of 1000 seeds and grain yield of peanut of experiment 17.

Peanut	1	2	3	4	5
1. Date of planting	1.000				
2. Yield of dry matter/plant	-0.664	1.000			
3. Number of branch/plant	-0.634	0.853	1.000		
4. Weight of 1000 seeds	-0.686	0.834	0.806	1.000	
5. Grain yield of peanut	-0.869	0.870	0.805	0.887	1.000

TABLE 6.10 The analysis of variance of the yield of dry matter of maize and peanut during the growth time of experiment 7.

Source of Variation	DF	Mean Square Maize	Mean Square Peanut
Block	3	0.0269	0.0155
Nitrogen fertilizer	3	6.7603**	0.0503**
Time	4	10.0437**	1.0684**
Nitrogen.Time	12	0.1224*	0.0277*
Residual	57	0.0315	0.0074
Total	79		

TABLE 6.11 The analysis of variance of leaf area index of maize and peanut during the growth time of experiment 7.

Source of Variation	DF	Maize	Peanut
Block	3	0.0006	0.0205
Nitrogen fertilizer	3	0.7018**	0.0129*
Time	4	0.3389**	0.4339**
Nitrogen.Time	12	0.0513**	0.0057
Residual	57	0.0033	0.0281
Total	79		

TABLE 6.12 The correlation matrices (r) of nitrogen fertilizer, nitrogen uptake, growth characters, yield components and grain yield of maize of experiment 7.

Maize	1	2	3	4	5	6	7	8	9
1. Nitrogen fertilizer	1.000								
2. Nitrogen uptake/plot	0.970	1.000							
3. Dry matter yield/plant	0.987	0.970	1.000						
4. Seed number/plant	0.966	0.933	0.967	1.000					
5. Weight of 1000 seeds	0.823	0.843	0.842	0.781	1.000				
6. Weight of cob	0.950	0.940	0.938	0.939	0.805	1.000			
7. Diameter of cob	0.896	0.866	0.905	0.896	0.828	0.783	1.000		
8. Length of cob	0.933	0.903	0.932	0.901	0.893	0.892	0.928	1.000	
9. Yield of grain/plot	0.972	0.924	0.949	0.902	0.804	0.843	0.872	0.916	1.000

TABLE 6.13 The correlation matrices (r) of nitrogen fertilizer, nitrogen uptake, growth characters, yield components and grain yield of peanut of experiment 7.

Peanut	1	2	3	4	5	6
1. Nitrogen fertilizer	1.000					
2. Nitrogen uptake	-0.833	1.000				
3. Dry matter yield/plant	-0.864	0.650	1.000			
4. Branch number/plant	-0.820	0.677	0.577	1.000		
5. Weight of 1000 seeds	0.390	-0.273	-0.231	-0.485	1.000	
6. Grain yield/plot	-0.866	0.710	0.818	0.740	-0.302	1.000

TABLE 6.14 The component LERs (L_{Cs}), LERs and the correlation coefficients (r) of two crop yields for all treatments in experiment 1.

Treatments	L_C cassava	L_C peanut	LER	r
Cassava (100%) + Peanut (25%)	0.991	0.148	1.139	0.012
Cassava (100%) + Peanut (50%)	0.983	0.271	1.254	0.583
Cassava (100%) + Peanut (75%)	0.956	0.397	1.353	0.094
Cassava (100%) + Peanut (100%)	0.933	0.491	1.423	-0.456

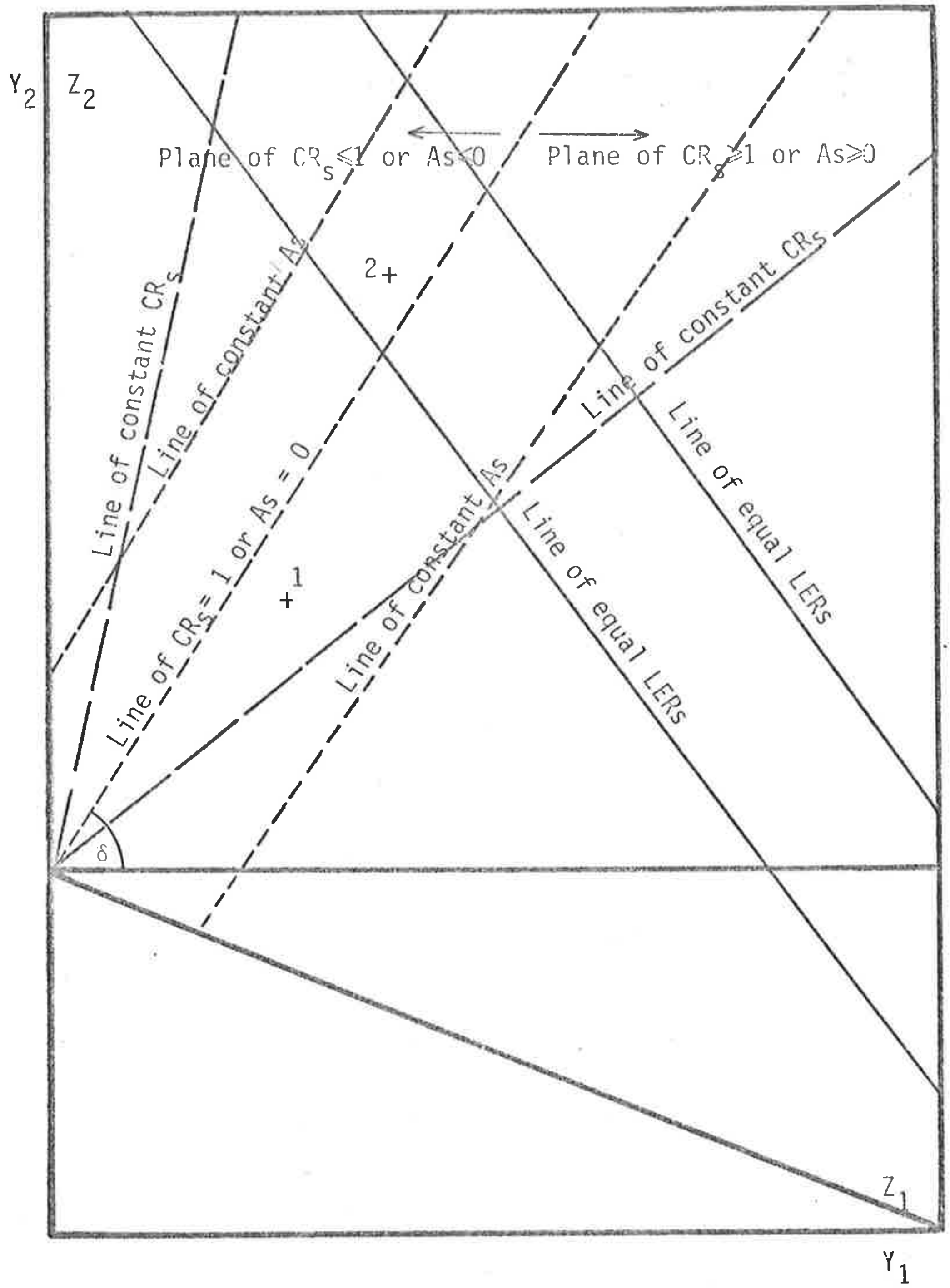

Fig. 6.1 Theoretical consideration of the two crop yields relationship in bivariate displayto show the constant lines of the degree of dominancy of the two crop yields and the line of equal LERs. (Points 1 and 2 are also two theoretical intercrop results).

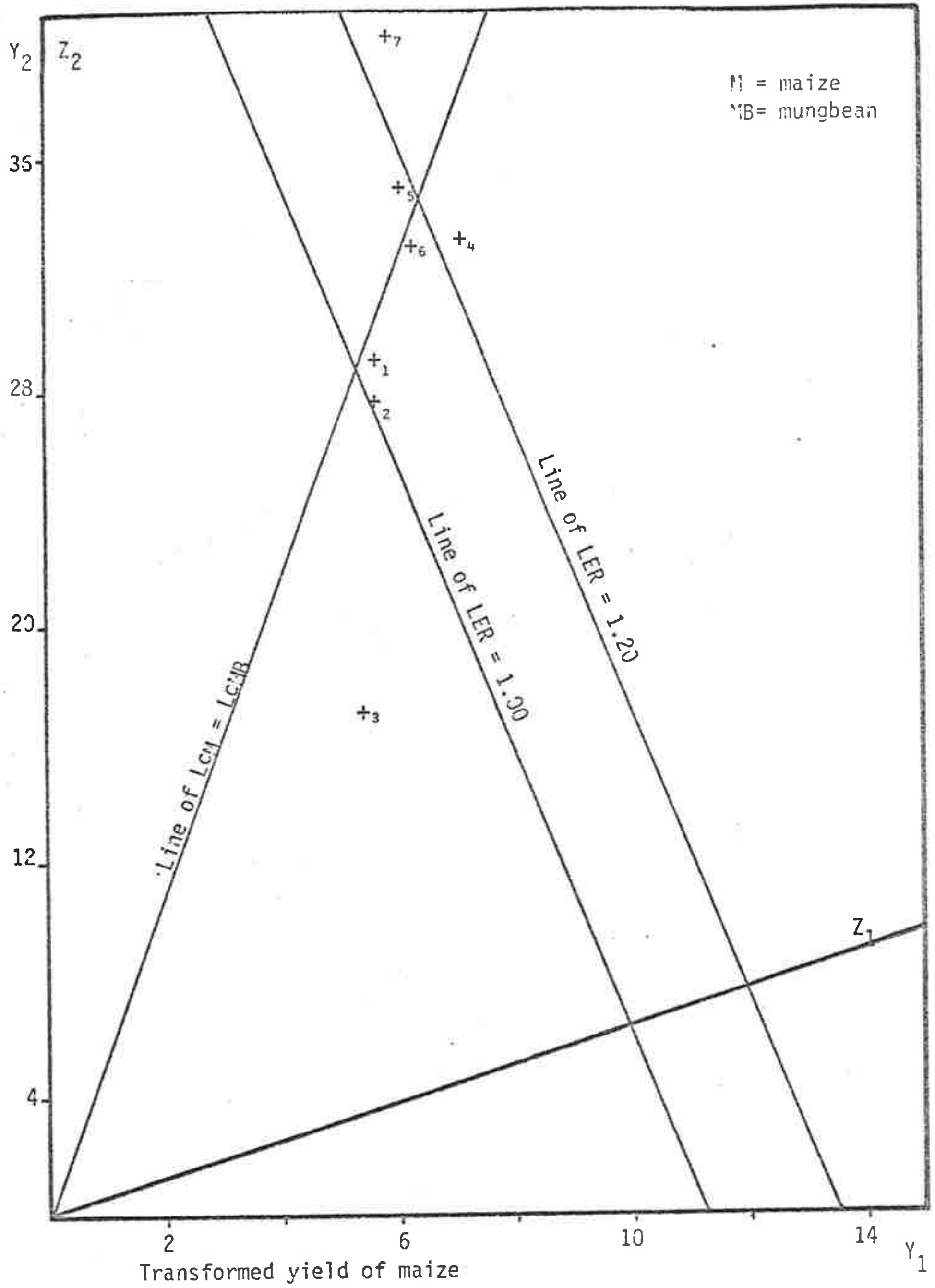

Fig. 6.2 The bivariate graphical display of experiment 8 to show the constant lines of LER and the constant line of the component LERs of maize and mungbean. 1 to 7 represent the number of mungbean genotypes.

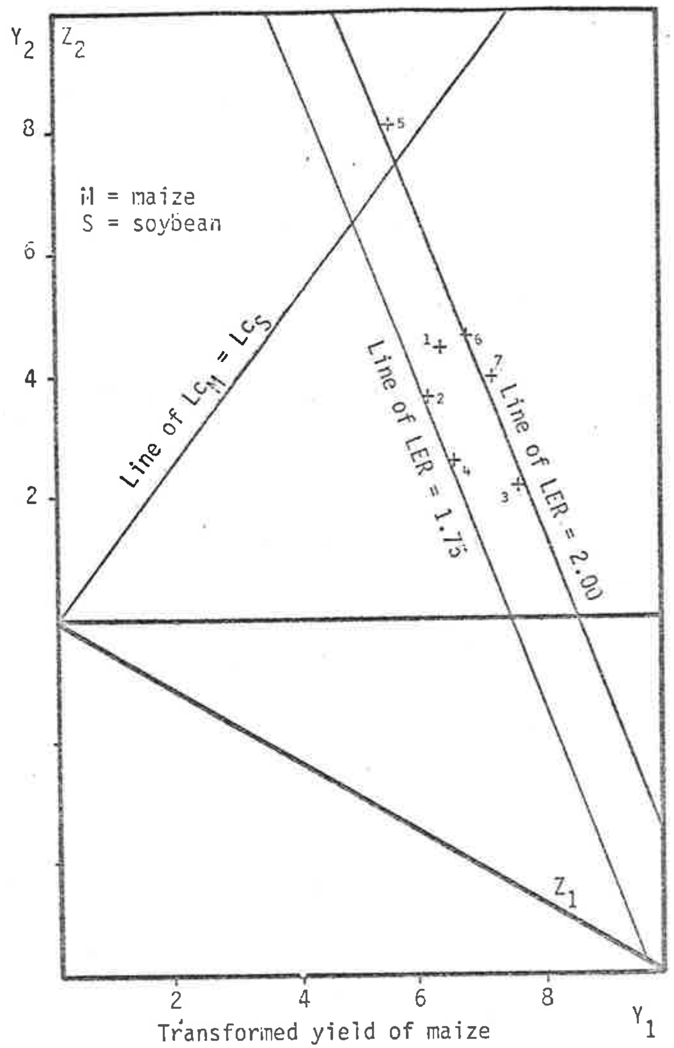

Fig. 6.3 The bivariate display of experiment 9 to show the constant lines of LER and the constant line of the component LERs of maize and soybean. 1 to 7 represent the number of soybean genotypes.

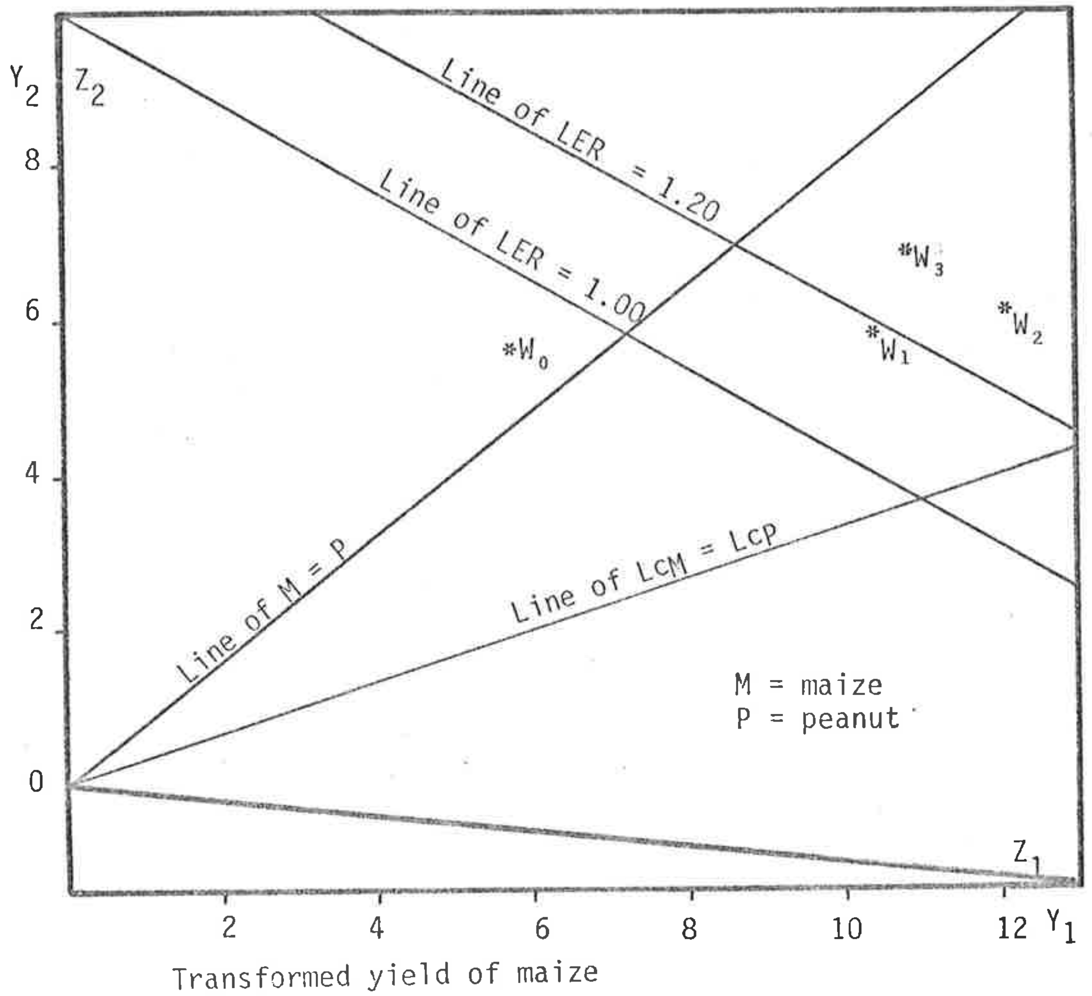

Fig. 6.4 The bivariate graphical display of experimen 16 to show the constant lines of LERs, the line of equal yields of maize and peanut and the constant line of the component LERs (Lc). W_0, without weeding; W_1, weeding by hand; W_2, weeding bay hock-hoe; W_3, weeding by herbicide.

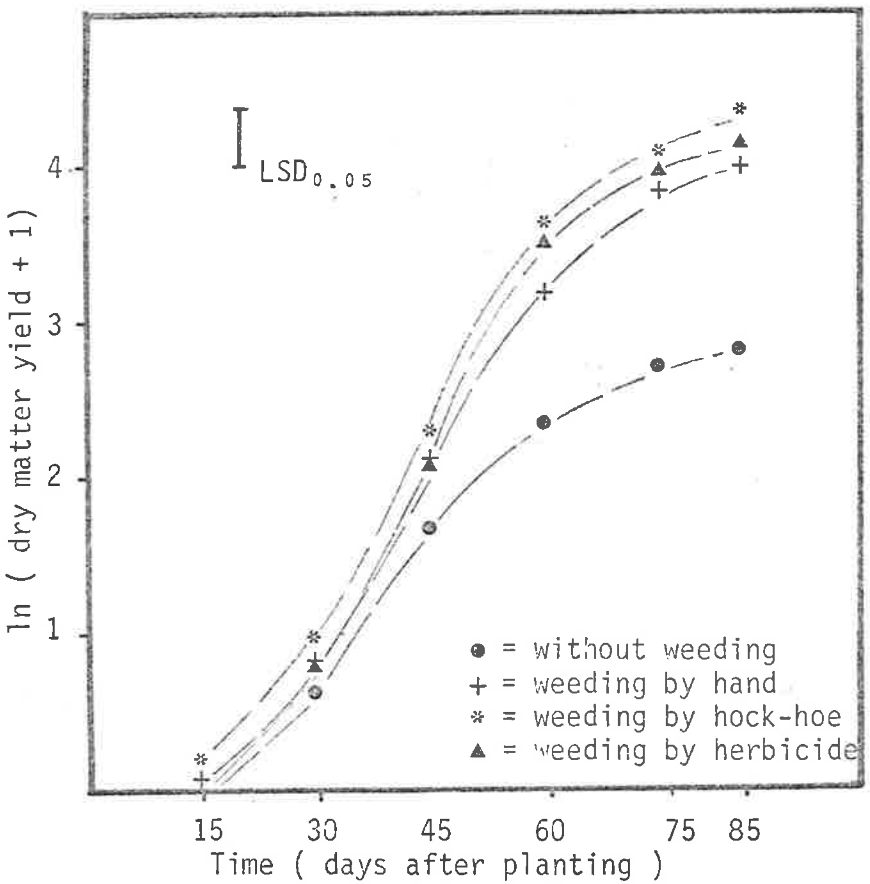

Fig. 6.5 The effect of weeding methods on the yield of dry matter of maize during the growth time of experiment 16.

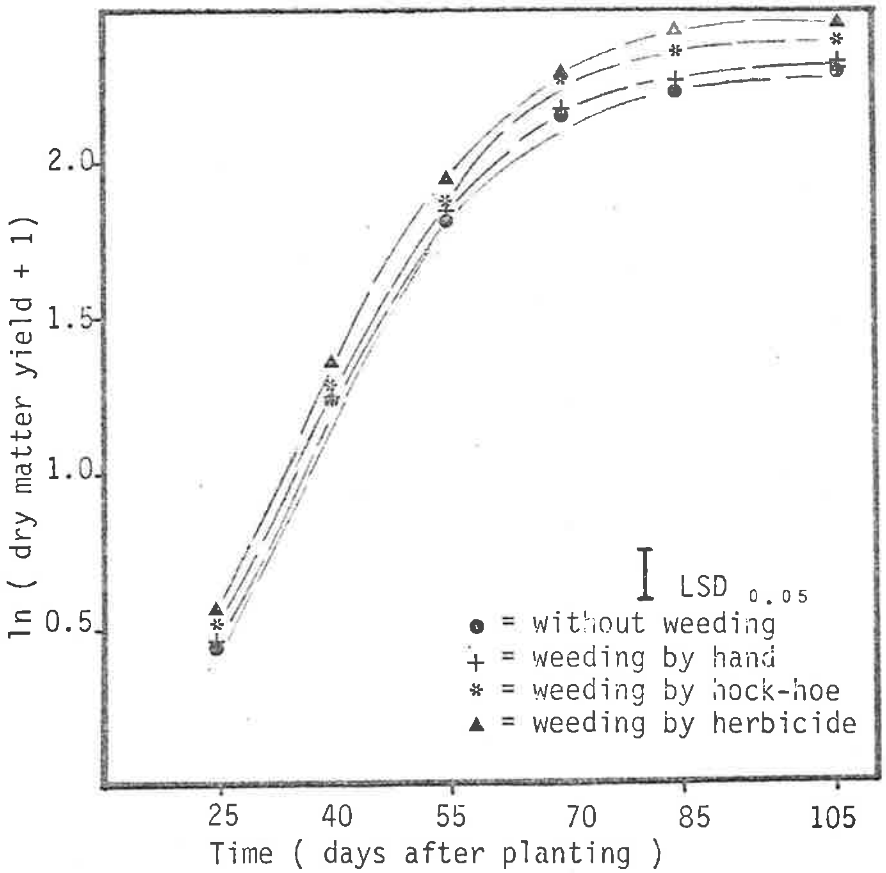

Fig. 6.6 The effect of weeding metods on the yield of dry matter of peanut during the growth time of experiment 16.

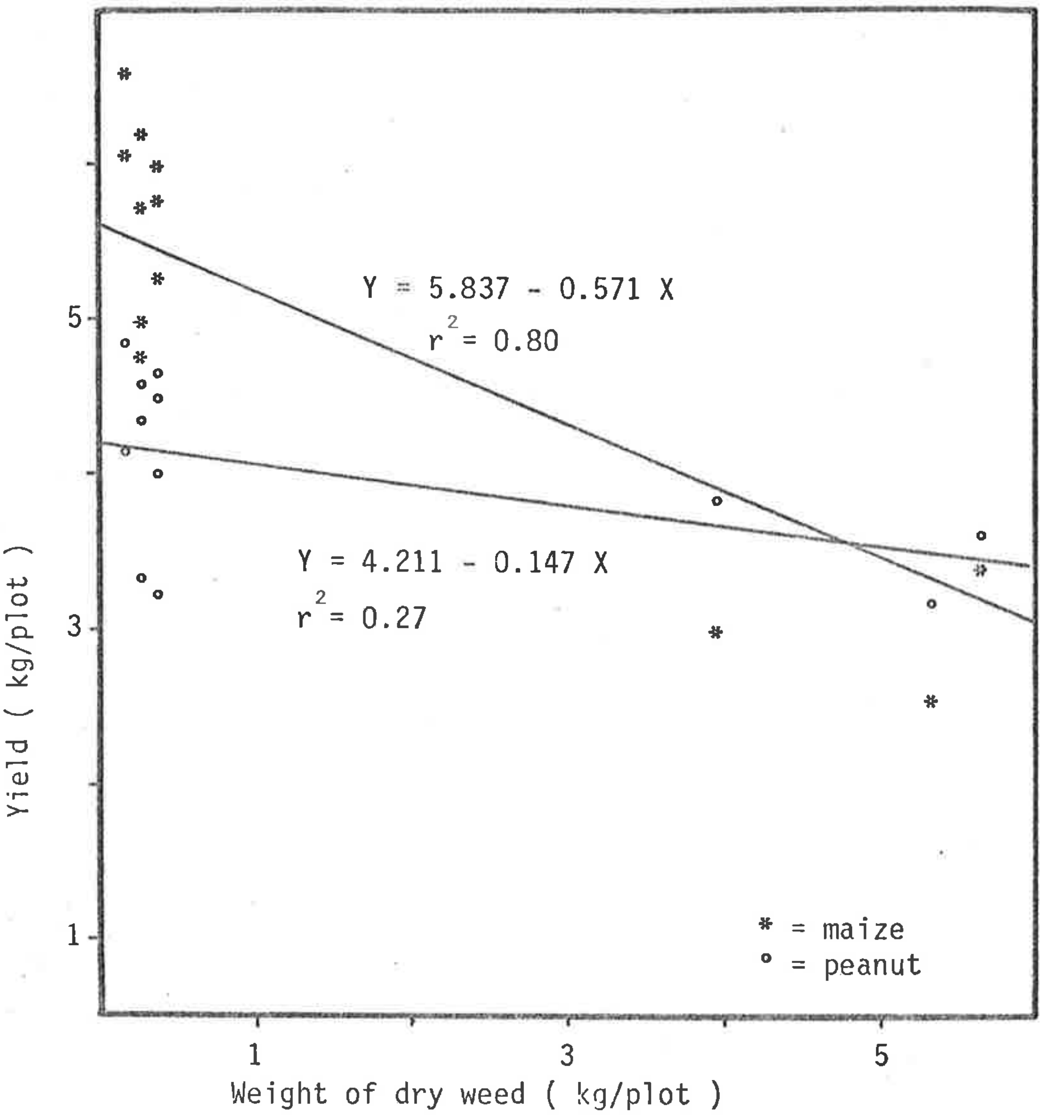

Fig. 6.7 The regression of weight of dry weed and the yields of maize and peanut of experiment 16.

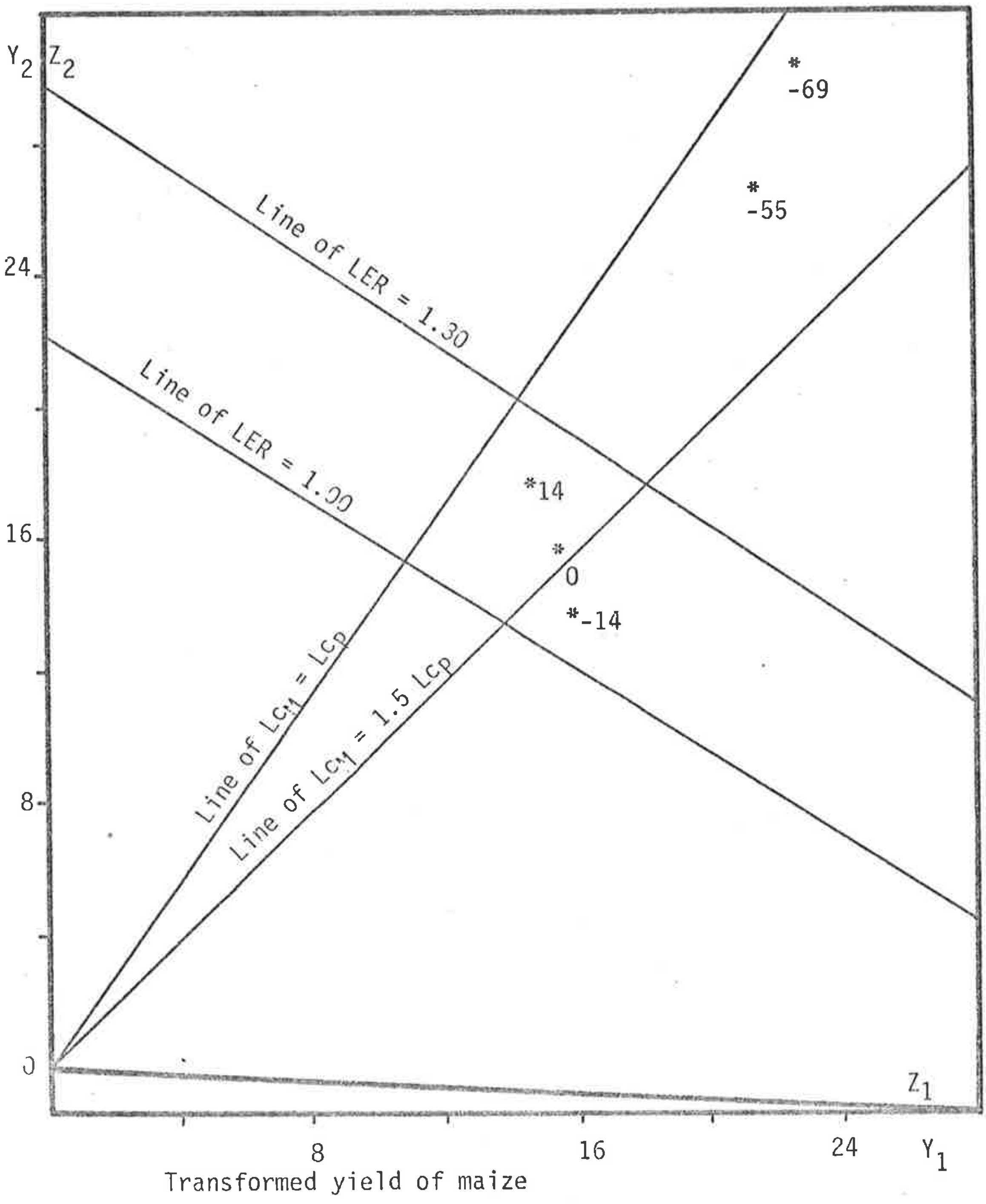

Fig. 6.8 The bivariate graphical display of experiment 17 to show the constant lines of LER and the constant lines of the component LERs of maize and peanut. -69, -55, -14, 0 and 14 are times of planting of maize in days before growing peanut.

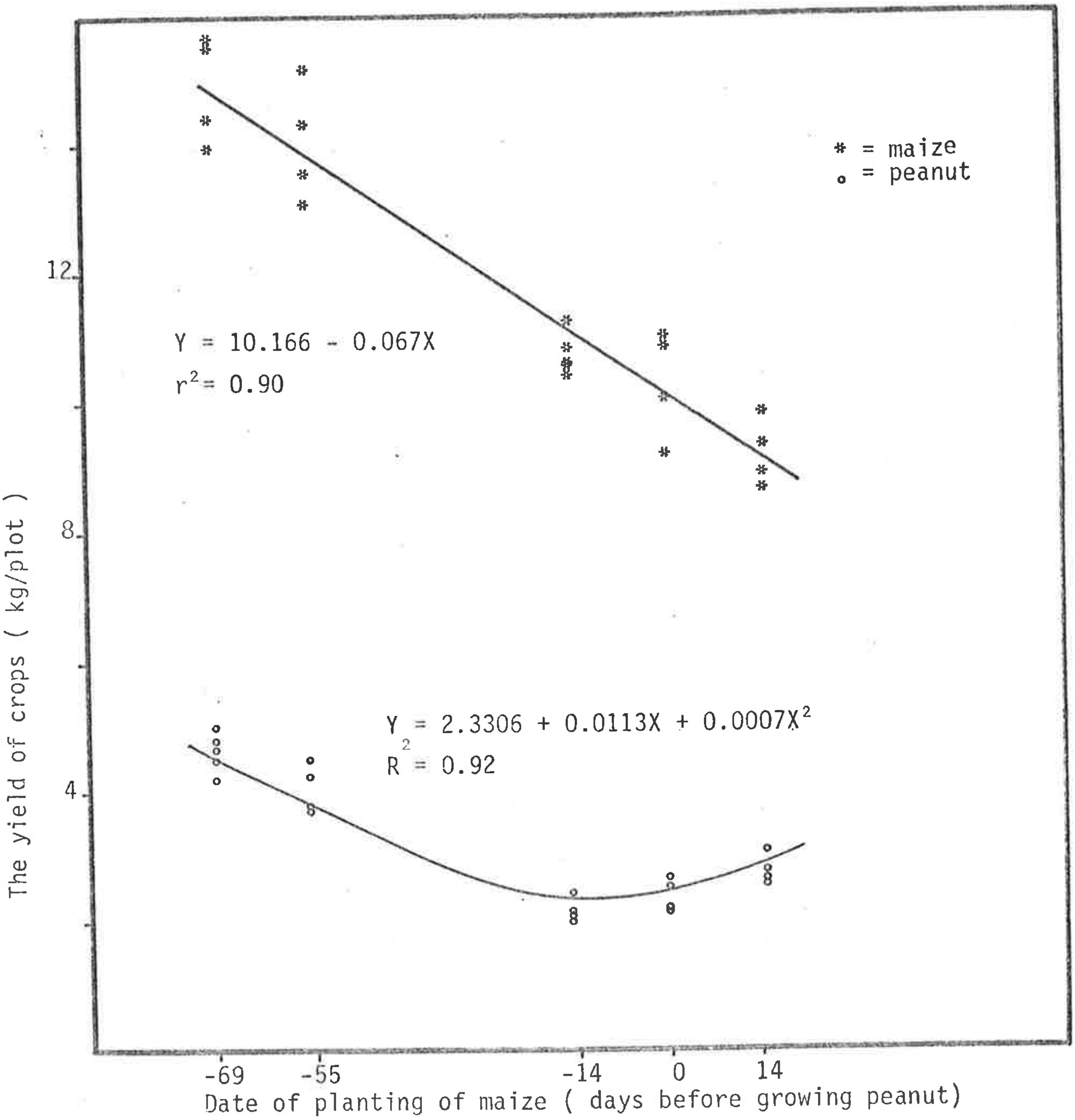

Fig. 6.9 The regression of date of planting of maize and the yield of maize and the yield of peanutof experiment 17.

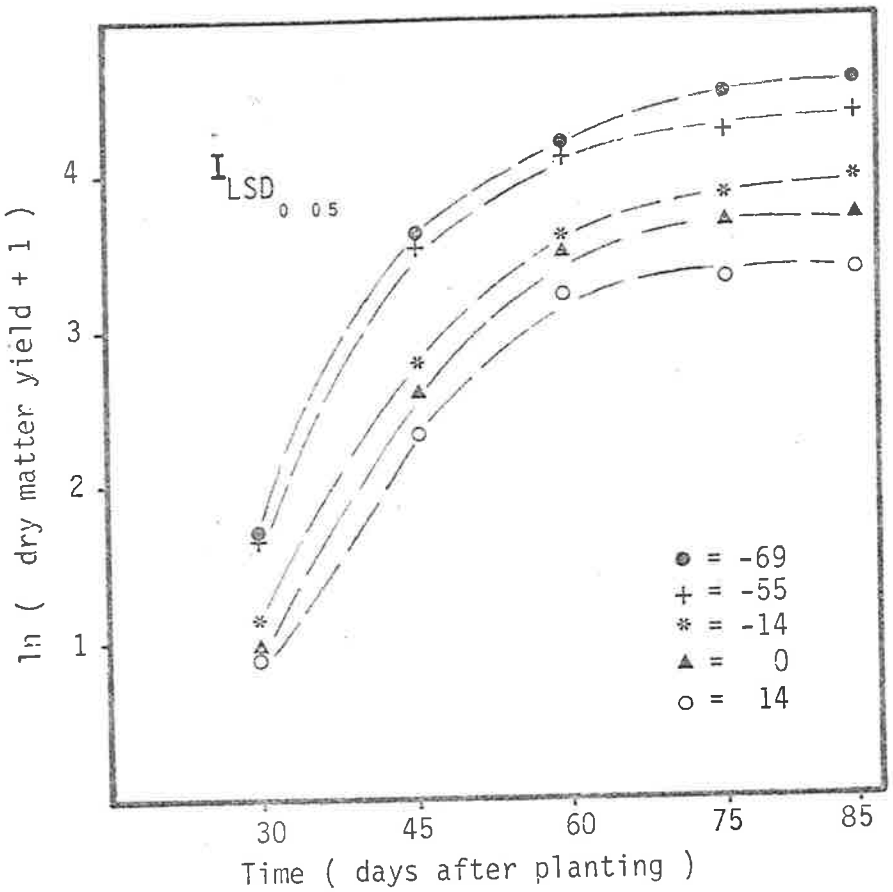

Fig. 6.10 The effect of date of planting of maize that is intercropped with peanut on the yield of dry matter of maize during the growth time of experiment 17. -69, -55, -14, 0 and 14 represent times of planting of maize in days before growing peanut.

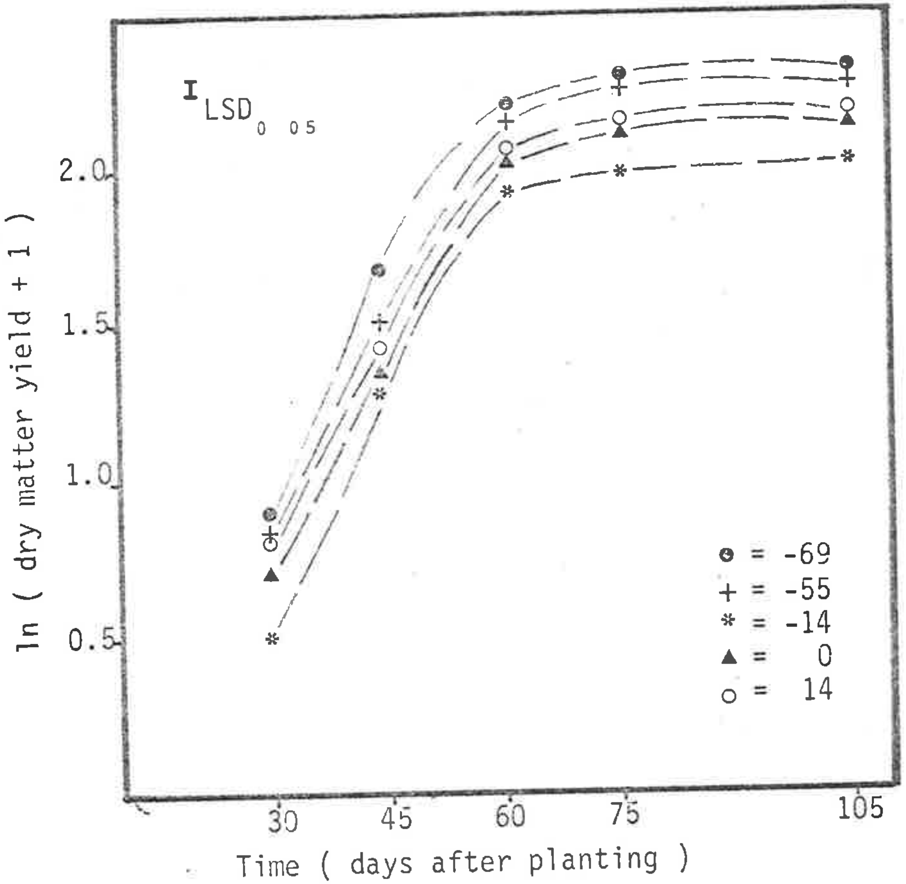

Fig. 6.11 The effect of date of planting of maize that is intercropped with peanut on the yield of dry matter of peanut during the growth time of experiment 17. -69, -55, -14, 0 and 14 represent times of planting of maize in days before growing peanut.

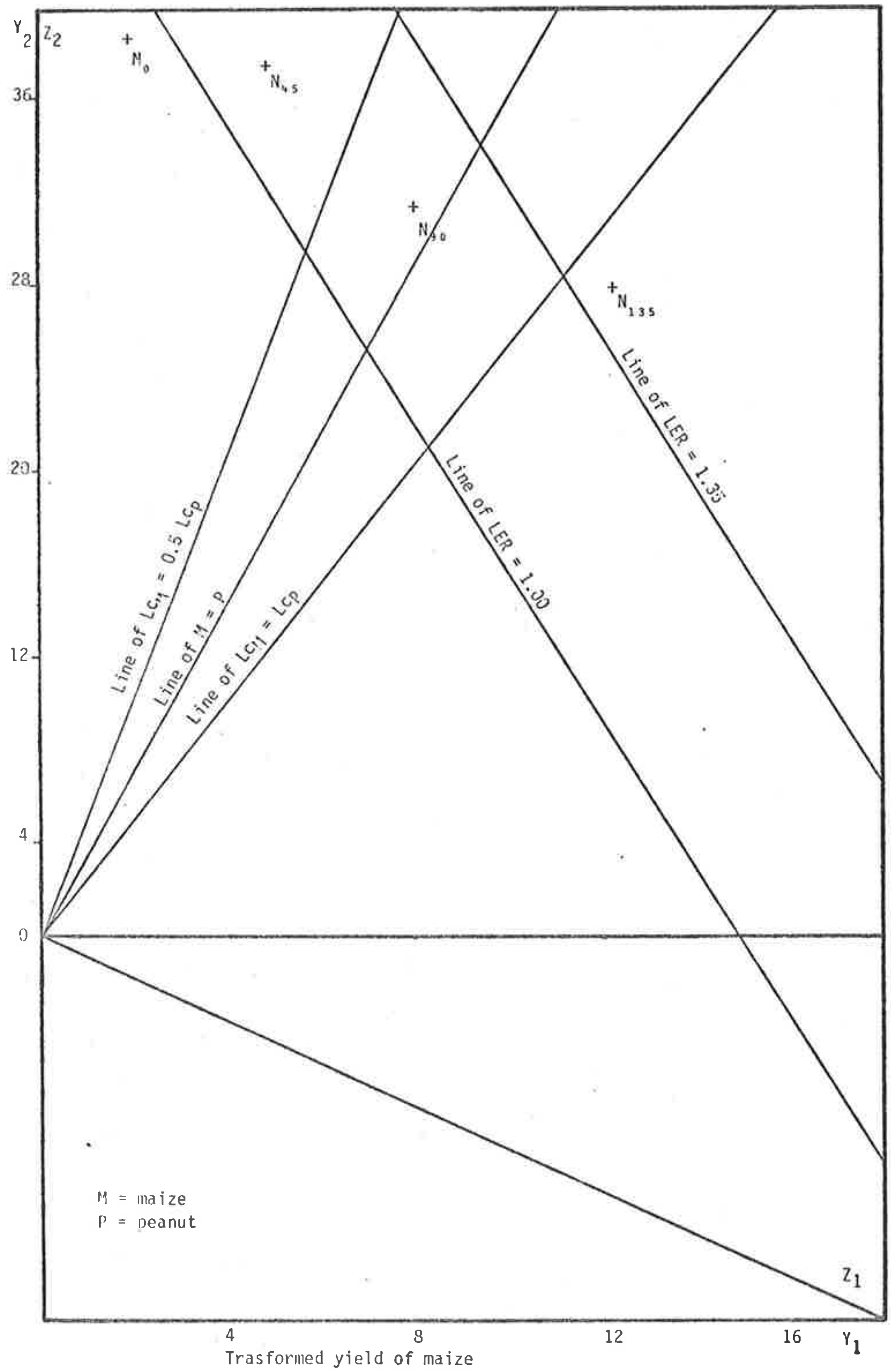

Fig. 6.12 The bivariate graphical display of experiment 7 to show the lines of constant LERs, the line of equal yields of maize and peanut and the lines of constant component LERs (L_C).

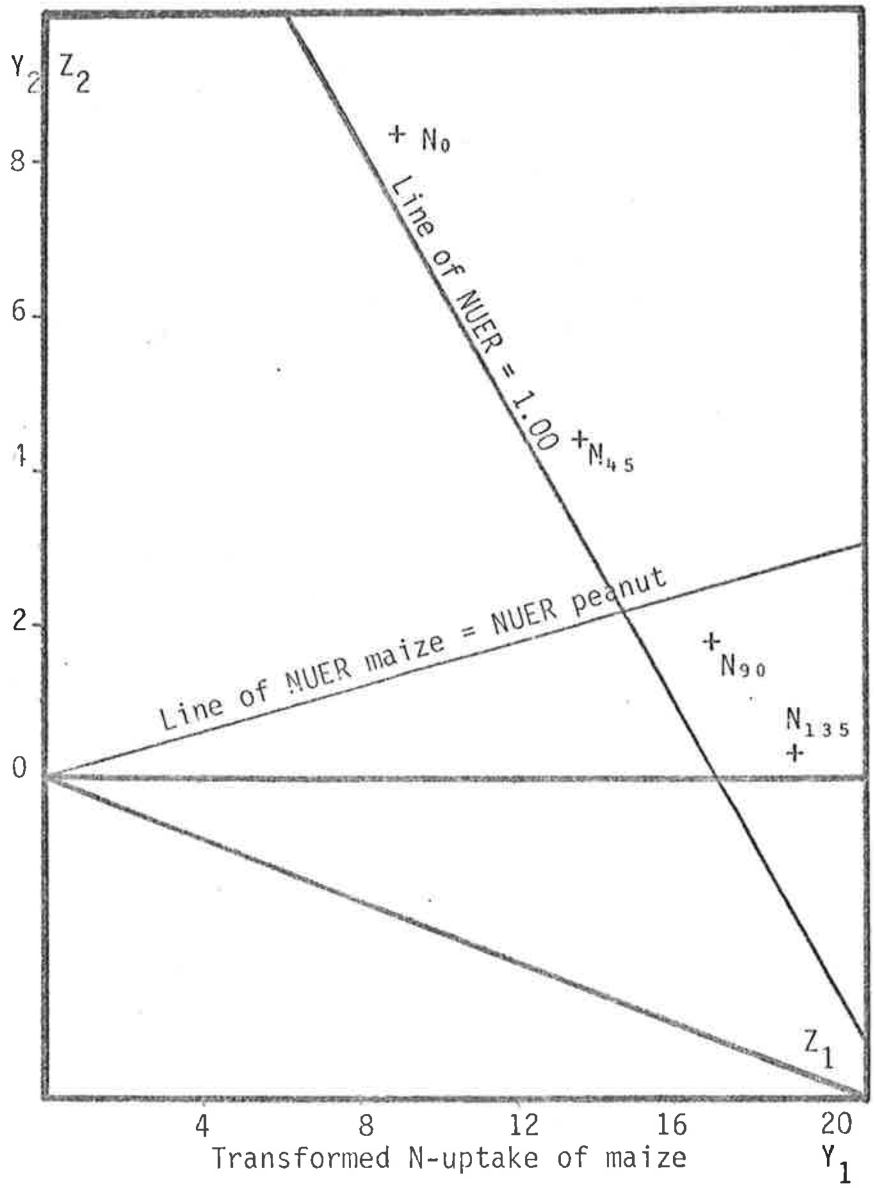

Fig. 6.13 The bivariate graphical display of experiment 7 to show the constant line of Nitrogen Uptake Equivalent Ratio (NUER) and the constant line of the component NUER of maize and peanut.

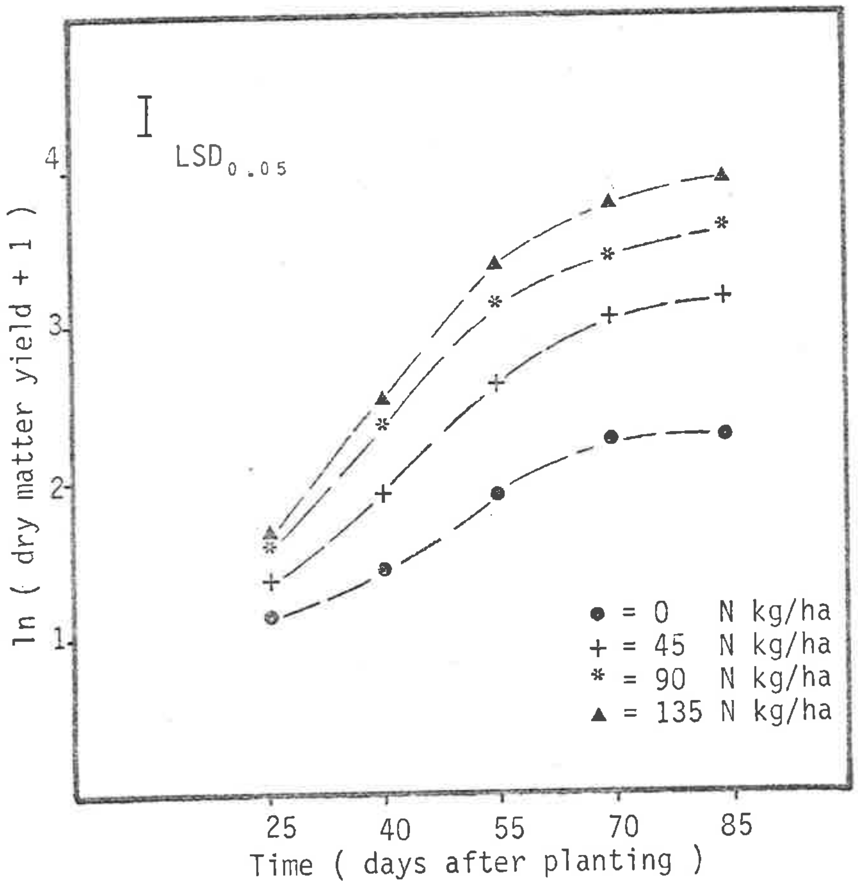

Fig. 6. 14 The effect of nitrogen fertilizer on the yield of dry matter of maize during the growth time of experiment 7.

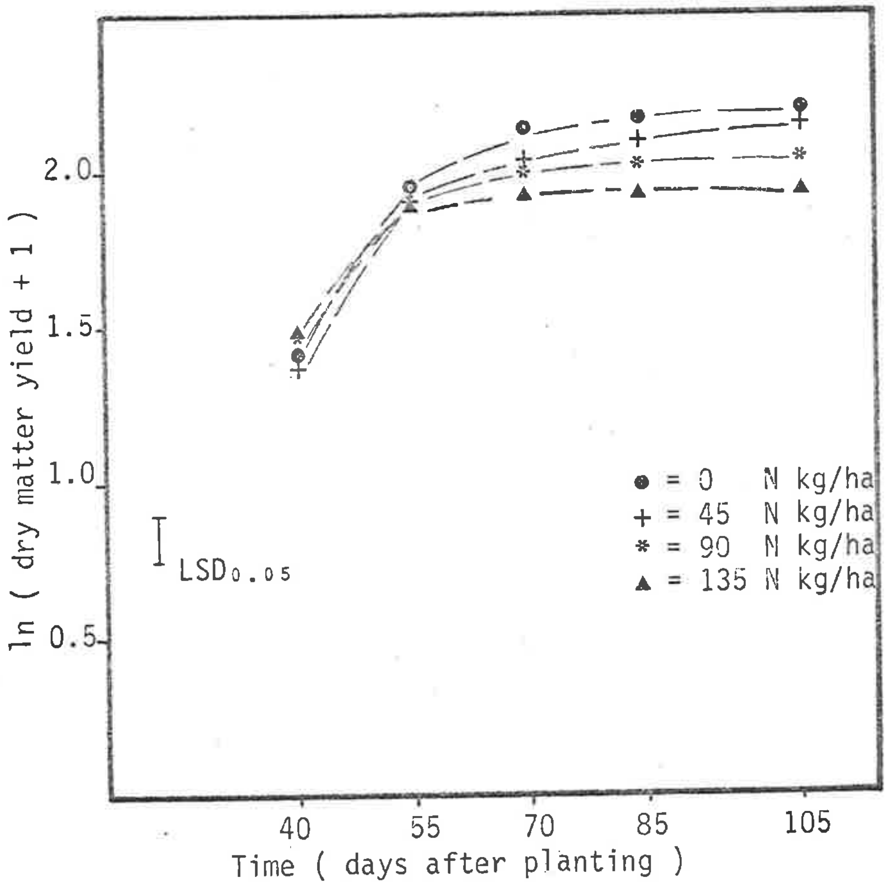

Fig. 6.15 The effect of nitrogen fertilizer on the yield of dry matter of peanut during the growth time of experiment 7.

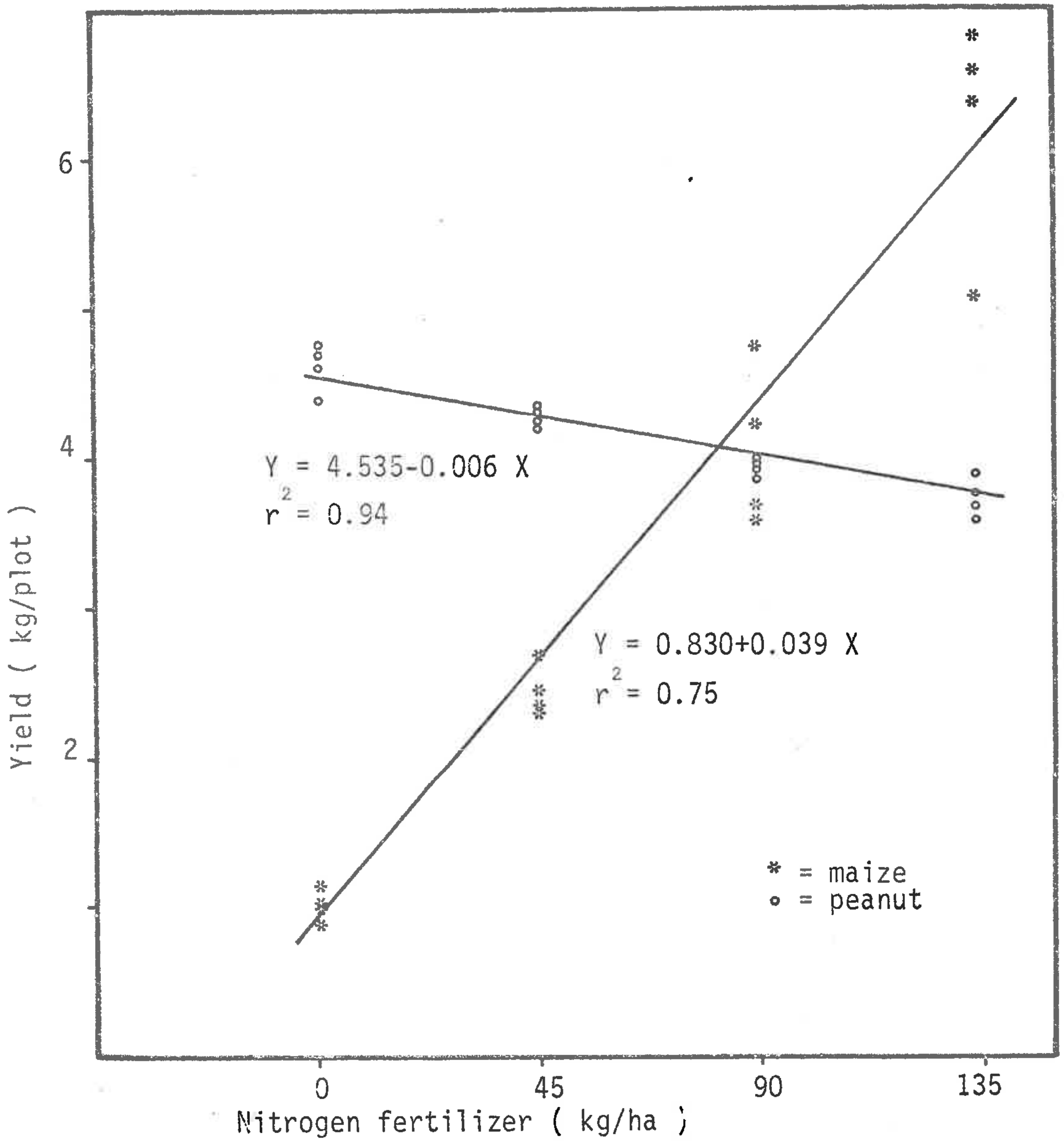

Fig. 6.16 The regression lines of nitrogen fertilizer on the yileds of maize and peanut of experiment 7.

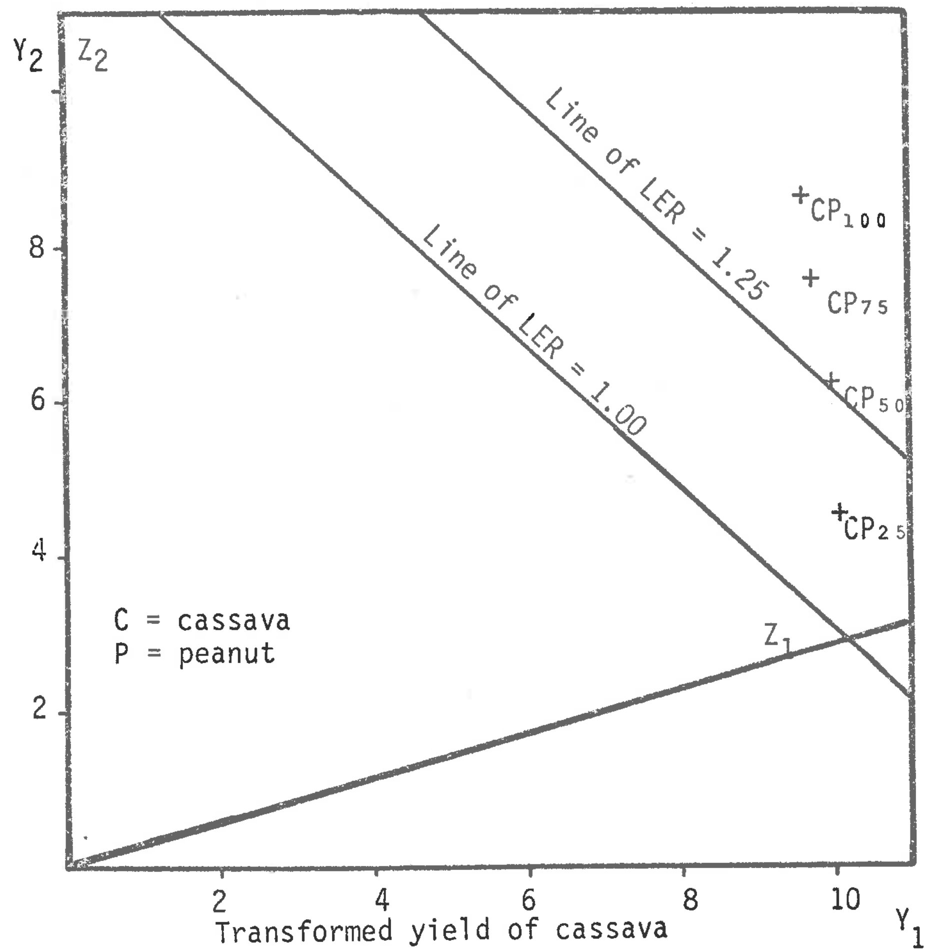

Fig. 6.17 The bivariate display of experiment 1 to show the constant lines of LER .

VII. EXPERIMENTAL DESIGN CONSIDERATIONS OF INDONESIAN INTERCROPPING EXPERIMENTS

1. INTRODUCTION

The intercropping practice is most prevalent in the tropics where temperature and moisture are suitable for field crop production during much of the year (Harwood and Price, 1976). Generally this practice is higher with smaller farm size as in much of Asia (Gomez and Gomez, 1983).

The Indonesian farmers, like the other farmers in Asian countries, are characterized by a diversity of crops and animals with small land holdings, generally less than 0.5 hectares, to be cultivated (Harwood and Price, 1976). With the rapidly increasing population and the shortage of new lands that can be cultivated in Indonesia, intercropping is expected to gain in importance (Ismail *et al*., 1978). This is because intercropping is a simple and inexpensive strategy for absorbing the rapidly increasing number of farm labourers (Gomez and Gomez, 1983).

Though intercropping practice has long been the norm for Indonesian farmers, research on this topic was only instituted in 1964 (Ismail, *et al*., 1978) and it has been increased by joint research with the International Rice Research Institute in the Philippines since 1974 (IRRI, 1973). A few years later (i.e. in 1968), the research on intercropped sugar-cane was initiated though not so popular during that time (Soegiyarto and Laoh, 1980). In 1975, the sugar-cane factories realized the difficulty of renting farmers land for sugar-cane plantations and also the Indonesian government's policy was to change the management of sugar-cane from the sugar-cane factories to farmers on their own land. By this system, the two problems were expected to be solved simultaneously. The first one, already mentioned, is the difficulty of getting land for sugar-cane plantations and the second, more importantly, is to increase farmers' income by cultivating sugar-cane on their own land. The problems are not so easy to solve, however, as already emphasized in Section III.2. The factories do not want short-fall of raw material through dependence on cane grown by farmers. On the other hand, the farmers do not want to diminish their own supplies of staple food, vegetables etc., or wait for a long time for payment from growing cane even though this can bring much benefit. Intercropping of sugar-cane with staple food crops or vegetables is expected to solve the two problems eventually.

Unlike the intercropping researches on staple food crops and beans or other vegetables conducted by the Research Institute for Food Crops at Bogor and its branches through Indonesia, the sugar-cane intercropping researches are only conducted by the Sugar Experiment Station at Pasuruan which is a non-goverment research institute. As a result, the volume of the intercropping research is also not as great as in staple food intercrops. How much intercropping research is carried out at Pasuruan mainly depends upon the urgent problems of sugar-cane factories (Soegiyarto, 1982). When it was shown that sugar-cane can also be grown outside of Java in places such as Sulawesi and Sumatra where the availiability of land is not an important problem, intercropping research on sugar-cane stopped for a while.

The intercropping practices of Indonesian farmers generally utilize local genotypes of crops and planting systems based on their own experience (Anonymous, 1978). As a result, the yields of the crops are generally low. The objectives of intercropping researches in Indonesia are similar to that in other countries, i.e. to identify the best combinations, planting systems, spatial arrangements, etc., of crops in order to get the maximum individual and combined crop yields.

This chapter summarizes Indonesia's intercropping experiments from the experimental design point of view and provides the experimental design rationale for Indonesia's intercropping experiments.

2. INDONESIAN INTERCROPPING EXPERIMENTS

As already mentioned in Section III.2, the experiments may be classified into two categories: (i) the intercrops of staple food crops with beans or other staple food crops and (ii) the intercrops of sugar-cane with staple food crops or vegetables. The summary of those two type of experiments is given in Table 7.1. From this table, it appears that in the first type of experiment the majority of intercrops (64%) consists of combinations of non-legumes (i.e. staple food crops) with legumes, where peanut (30%) and soybean (25%) are predominant, as the associate crops for maize or cassava. Maize and cassava are mainly for staple food while the beans are mainly grown for sale. This type of intercropping (i.e. non-legumes and legumes) has an expectation of substantial benefit through the complementary effect of legume crops. However, intercropping of non-legumes could still be expected to yield benefits from the different root zonation of the two crops which gives differences in exploring nutrient or water from the soil (Snaydon and Harris, 1979). The sugar-cane intercropping experiments show different results in that intercrops with non-legumes are greater than with legumes. This fact is considered in the previous section and in Section IV.2, regarding the objective of the research. The two objectives of production that should be considered are the requirements of food by farmers and the requirement of raw material by sugar-cane factories. Hence, the researchers should be aimed to determine not only how to get the maximum of sugar-cane yield but also how to get some additional yields of staple food crops or associate crops.

Most experimenters tend to exclude the sole crops in their experiments, (Table 4.2.24 in Section IV.2), which means they are only interested in comparing between intercrop treatments. From Table 4.2.24, also it appears that in most sugar-cane intercrops (i.e. experiment 39 to 51) it is necessary to have sole sugar-cane as a control. This is because the aim of these experiments was mainly to maximize full yield of sugar-cane with some additional yield of one or more other crops (see Section IV.2).

Though the experimenters regard sole crops as controls, they include the sole crops within the randomization scheme (Fig. 7.1). The effects of border rows are mostly allowed for, as indicated in the layout of experiments in Fig. 3.2.1 to 3.2.4, though the reason for having border rows is of course precautionary given the limited experimental evidence available for intercrops. This probably accounts for most experimenters using two rows as borders for all crops.

The types of intercrops, treatments or test factors and experimental designs mostly used for Indonesia's intercropping experiments can be seen in Table 7.2. Examination of the first type of experiment reveals that maize is the major main crop, intercropped either with beans or upland rice or sweet potatoes. The intercrop with cassava is not so widespread at the moment though this crop may well be substituted for maize or rice in the future time. Cassava research in Indonesia has been conducted in the Faculty of Agriculture of Brawijaya University at Malang since 1975 under the sponsorship of IDRC in Canada and it is mainly concentrated on sole crops, though this program now has been changed to cropping system research (including intercropping research) on cassava. From Table 7.2, it also appears that a primary aim was to identify the suitable genotypic combinations and population densities of the two crops. Fertilizer, spatial arrangement and management of crops (i.e. leaf cutting treatments) have also been important problems. The experimenters appear to have different views on numbers of treatments and numbers of replications. On the one hand, some choose small numbers of treatments, but larger numbers of replications, and on the other, the reverse has been used. The most frequently used design is the

Randomized Complete Block, the other being the Split Plot Design. When the number of treatments was ≦ 12, experimenters generally used the Randomized Complete Block and if the number of treatments was greater than 12 then Split Plot Design would be considered.

From Table 7.2, in sugar-cane intercrops in general the number of treatments was small (i.e. ≦ 6). The most important test factors were the different possible associate crops for sugar-cane, population densities and fertilizer treatments were also of interest. All experiments used the Randomized Complete Block Design with four or more replicates depending on the number of treatments involved.

The plot size and coefficient of variation (reproduced from Table 4.2.5 and 4.2.7) are presented in Table 7.3. Plot size varied considerably among cassava intercrops, maize intercrops and sugar-cane intercrops and was, as would be expected, larger for sugar-cane intercrops. The shape of plot was generally rectangular rather than square. As we have already noted, not all experiments had sole crops, the experimenters clearly not concerned with sole crop yields in each site. Hence, we only consider the coefficient of variation of each crop analysis and the combined yields in terms of the first crop yield equivalence, though the latter varies with the market situation. Hence, it is very difficult to make the precise comments on the effect of the shape and size of plot on the variability of experiments. The experiments differed not only on the type of intercrop, but also the treatments involved, the site and the seasons. Nevertheless, this study indicates the general views of experimenters on plot size and shape effects, and suggests that at least a few uniformity trials should be conducted in Indonesia.

Table 7.3 on the cassava and sugar-cane intercrops suggests that the effect of plot size on the variability of cassava or sugar-cane yields is not so great (see Section IV.2) on maize yields, on the other hand, the effect of plot size was greater, through the influence of the associate

associate crop. For example, in experiment 12 and 13, where the plot size was the same and the experiment differed only in the second crop, the variability of maize in experiment 12 was much greater than in experiment 13. Considering the coefficient of variation of the combined yields in terms of the first crop, yield equivalence from Table 7.3 together with the plot size, one notes that the coefficients of variation between experiments are also variable. In most cases, the coefficients of variation of the combined yields were small which could be the result of the compensation between the two crop yields (see Chapter V). Examining the repeated experiments (i.e. within a, b, c, d, e or f), with the same plot size, one concludes that the plot size effect on the coefficient of variation of each crop analysis and the combined yields is also variable between sites and seasons. These results indicate that different plot sizes or plot shapes in different crop combination and sites or seasons as well will be needed, but what actual values have yet to be determined.

Table 7.4 presents the summary of the effect of blocking on the reduction of the experimental error (i.e. calculated as Pearce, 1978, 1980). The coefficient of variation in each experiment was calculated by allowing for treatments, but making no attempt to control environmental variation, and these results may be compared with the coefficient of variation of Table 7.3 (i.e. the ordinary coefficient of variation according to the appropriate models). It appears that in general, as expected, the coefficient of variation with blocking is smaller than without blocking, though the efficiency of blocking in most cases is rather small. The efficiency of blocking is variable not only between the types of intercrops (i.e. between cassava intercrops, maize intercrops and sugar-cane intercrops) themselves, but also within the same type of intercrop as well. Consider for example cassava intercrops where only experiments 1 and 33 show any considerable gain in efficiency in using blocks and experiment 2 shows none. The same results also appear in maize intercrops and sugar-cane intercrops. This indicates that the improvement in efficiency from blocking in Indonesia's intercropping experiments is generally only marginal, given the plot sizes and shapes which have been used.

3. DISCUSSION

Intercropping experiments required the development not only of statistical analysis but also of designs (Anonymous, 1973). These must allow the simultaneous testing and evaluation of several crops following a prescribed combination or sequence of planting. Thus, instead of being concerned only with environmental influences on a single crop, one requires a technique by which many types of crops and crop sequences can be tested under different environments (Anonymous, 1973 and Mead and Stern, 1979, 1980). As a result, the total numbers of factors to be tested in intercropping experiments are generally large. Experiments would need to be even larger if there were to be the same number of sole crops as well as of intercrop treatments. As noted earlier, Indonesia's experimenters already realize that the important aim is to get the best combination between intercrops (see Section IV.2). Thus, the sole crops are regarded as controls like the untreated plots of insecticide or fertilizer treatments in sole crop experiments (Mead and Stern, 1980). Consequently the function of sole crops is regarded as the provision of background information in which case it can be argued that they should not be randomized with the intercrop treatments nor should their results come into the main part of statistical analysis (Freeman in the discussion on Mead and Riley, 1981). It appears, however, from the previous section that though the experimenters regard sole crops as controls, they include them in the randomization processes with intercrop treatments. Another problem in the inclusion of sole crops in the randomization with intercrop treatments is the effect of crops which are different in height. For example, in intercropped cassava and peanut as in Fig. 3.2.1, the placing of a sole peanut plot in the middle of cassava plots may not be appropriate as peanut will be shaded by cassava. Thus, the performance of sole peanut when surrounded by cassava would be different from the actual sole peanut in the open field. Again, these arguments show how sole crops should be placed and what their function is in intercropping experiments (Mead and Stern, 1980). Let me re-emphasize, as also in Chapter V, that intercropping is an old idea, so that our goal is to get the best combination of the crops not to persuade farmers to grow intercropping systems. Further, if it is desired to have precise information of sole crop performance in certain sites or seasons, then sole crop plots outside of the main treatments would be suitable and these could be larger and not necessarily repeated the same as the intercrop treatments.

In general, the number of treatments is small and with sugar-cane, very small. This is in contrast with the theoretical consideration of intercropping treatments, since the number of treatments would be at least twice as great as in sole crops (Mead and Stern, 1979, 1980). As regards treatment structure, one can discern two different approaches. One experimenter modulated the second crop by varying population density or date of planting in order to get maximum yield of the first crop, so in general using non-factorial structure. The other experimenter, however, varied the two crops simultaneously so the number of treatments was larger though even so, usually less than 15. The reason for having small numbers of treatments in each block probably derives from Yates (1935) who demonstrated the advantage of using small blocks in field experiments.

Despite many important changes in field experiments since then, small blocks still yield worthwhile gains in efficiency

(Patterson and Ross, 1963). Hence, the most rewarding developments for intercropping experiments will probably relate to factorial structure (Mead and Riley, 1981). The advantages of factorial structure have been emphasized cleary by Cox (1958): precision for estimating overall factor effects; enabling the interactions between main factors to be exploited; and allowing the range of validity of the conclusions to be extended by the insertion of additional factors. Section IV.2 shows that in most cases the interaction terms were not significantly different from zero. This absence of interaction is a strong argument for factorial structure given the other advantages of factorial design through the hidden replications (Mead and Riley, 1981; Mead, 1983).

The importance of size, shape and position of a plot in reducing the experimental error have long been recognized in sole crop experiments (Kalamkar, 1932; Smith, 1938; Gomez, 1972; Reddy and Chetty, 1982). Plot size not only affects the variability of experiments, but also causes bias in the experimental result (Gomez, 1972). From the results of the same experiment, in different sites or seasons, though the plot size remains the same, the experimental error can be quite different. This result was also obtained by Smith (1938) who emphasized that the plot size needed to reduce between plot variation differed between sites and crops. It was noted in Chapter V that the variability of crops is greater in intercropping than in sole crops. Hence, the plot size for intercrops should be larger than for sole crops and probably additional replication is required to obtain the same precision as for sole crops (Davis, Amezquita and Munoz, 1981). They also showed that border effects were not uniform among genotypes of crops. Thus specific plot sizes and border arrangements are necessary for intercropping experiments to yield their most useful results. Clearly the plot technique used in intercropping experiments should incorporate the agronomic requirements of each crop (Gomez and Gomez, 1983).

The results of the previous section show that in most cases blocks were succeeded in reducing the residual experimental variability (i.e. the coefficient of variation), though the gain was usually only marginal. This was also concluded by Pearce (1978, 1980) who studied maize under tropical conditions. Hence, most experimenters know little of the pattern of soil heterogeneity of their experiment. It is well known that the usefulness of blocks depends on how much thought has gone into their information. If the experimenter divides his land without careful consideration, he will probably do harm as the blocks run in the wrong direction relative to the soil fertility. Instead of forming blocks that are homogeneous, he may put together plots that are clearly diverse (Pearce, 1978). Hence, knowledge of soil fertility patterns in the field is vital to the success of the experiments.

The consideration has had a further influence on experimental design in that Split Plot Designs were used only to simplify allocating treatments rather than to further the experimental objectives. Consider experiments 8, 9, 22, 23 and 24, where the main plots contain the treatment of planting systems (i.e. either sole crops or intercrops). In this case, the sub plots merely allow the easier allocation of the treatments (see also Baker in the discussion of Mead and Riley, 1981). Hence, the gain in efficiency in the experiment may be expected from Randomized Complete Block rather than from the Split Plot Design, if experimenters realize what the function of sole crops and how they should be treated (Mead and Riley, 1981). The necessary assumption in using Split Plot Design for intercropping experiments should be that some factors require a large plot while others do not (Mead and Stern, 1980). The other considerations and how the Split Plot Design should be used are treated comprehensively by Federer (1975).

4. GENERAL CONSIDERATIONS IN DESIGNING INDONESIAN INTERCROPPING EXPERIMENTS

Indonesia, as a developing country, is not much different from the others where statisticians or biometricians are a luxury (Gomez, 1983). As a result, experimenters in order to choose the appropriate field design, may simply adopt the results of the research from developed countries. This, however, is not always appropriate since the conditions of land used for research in developed countries is different from those in developing countries (Pearce, 1983). The experience on the requirements of different plot size or plot shape for different sites or seasons (Smith, 1930; Reddy and Chetty, 1981) shows that it is required to stock of data from a uniformity trial.

In these early stages of development of intercropping experiments, we should assess the experiments from first principles (Mead and Riley, 1982). The adoption of designs for sole crop experiments may not always be appropriate for intercropping systems. Border rows, plot size and plot shape should also be developed for each crop combination and sites or season as well. Unnecessary borders rows and excessive plot size for a certain crop combination will waste the experimental material, while absent border rows or inadequate plot size may disturb the result of experiments. My investigations reveal that experimenters tend to use the same number of rows for borders without considering the type of crop combination and this may not be appropriate (Gomez and Gomez, 1983). That rectangular plots are usually better than square plots should also be realized (Kalamkar, 1932; Reddy and Chetty, 1982). Again, different crops generally have different degrees of variability (eg. maize is less variable than sweet potatoes) so that the requirements of size of plot or plot shape, border rows and number of replications will also differ for each crop combination. Thus, one must consider the main objectives of the research in choosing the appropriate plot size and shape, etc., to reduce the variability of the experiments. If one crop is more important (i.e. main crop) then its variability is of primary concern, whereas if the importance of the two crops is similar then the crop with the greatest variability should be considered (Gomez and Gomez, 1983).

The usual way of reducing the experimental error by local control is to divide the area into blocks which are as internally homogeneous as possible (Fisher, 1921; Pearce, 1978, 1980). This is easier said than done, of course, soil heterogeneity being so unpredictable (Sanders, 1930; Pearce, 1978, 1980). The result of this study is that though blocks are generally effective in reducing the experimental error; the improvement is only marginal and disappears in some experiments. This indicates how important is the prior knowledge of the experimenters of the soil heterogeneity of their field. Ideally, where no past records are available especially, he should be able to walk over the site and study its pattern, in which case he may be able to form effective blocks or perhaps decide to use rows and columns design or even adopt a completely randomized design by realizing that the site is extremely uniform (Pearce, 1978).

In order to maximize efficiency, it is important to re-emphasize that sole crops versus intercrops is not a true treatment comparison (Mead and Stern, 1980). Then the task to be handled in intercropping experiments is clearer and not mixed with the sole crop problem. As I have emphasized, in intercropping experiments, it is necessary to examine the interaction among factors not only within individual crops, but also between component crops. Hence, experiments may be too large to be handled efficiently in one phase as in sole crop experiments (Gomez and Gomez, 1983). Consequently, the experiments should be carried through more than one phase, the first with large factors but small levels so as to identify the magnitude of interactions among the factors. In the next stage, one seeks to differentiate between factors that show interaction or no interaction. For the factors that show no interaction, a single factor experiment can be used if appropriate on other grounds, whereas those with large interactions should be carried out in multifactor experiments with smaller numbers of factors, but more levels for each factor (Gomez and Gomez, 1983). This shows the important short comings of the previous intercropping experiments with small numbers of treatments in each experiment.

For factorial experiments, designs have been developed such that the number of replications can be minimized (i.e. Partially Replicated Designs) or such that not all the factorial treatment combinations have to be included (Fractional Factorial Designs (Yates, 1937; Cochran and Cox, 1957; Gomez and Gomez, 1983). The use of these designs may not be so easy for the non-statistician especially in choosing which factors should be confounded to arrive at a specific incomplete factorial structure. It has been emphasized earlier that the use of experimental designs should not be determined by such possible practical problems (Mead and Riley, 1981). Thus, in order to get better results from intercropping research, the experimenters and statisticians should work together in using advanced statistical theory.

The other approach to the reduction of experimental variability is to reduce plot size by eliminating border rows by using systematic designs (Nelder, 1962; Mead and Stern, 1979, 1980). The major advantage of systematic design is the great economy in both land area and experimental material. On the other hand, systematic designs have also some disadvantages since the lack of randomization makes estimation and hypothesis testing of parameters inappropriate. Other difficulties can arise from systematic arrangement: if there is an environmental gradient in the experimental area then the estimates of treatment effects may be biassed; and the residuals may be correlated, with a correlation matrix that is usually unknown (Lin and Morse, 1975). Therefore it is important to underline the danger of these designs sufficiently to experimenters who are relatively unfamiliar with the theory of experimental design (Nelder in the discussion of Mead and

Riley, 1981). Nevertheless, the advantages of systematic designs are considerable and the option of using them should remain where appropriate (Nelder, 1962; Huxley and Maingue, 1978; Mead and Riley, 1981; Willey and Rao, 1981). The important fact that should be realized by the experimenter in using systematic designs is that the aim is to get a general idea of the shape of a curve rather than to estimate particular parameters.

The debate concerning the relative efficiency of randomized versus systematic layouts has persisted since the controversy between Fisher and Student (Fisher, 1926; 1936; Gosset, 1936; Barbacki and Fisher, 1936; Studnet, 1937). This has been reviewed by Wilkinson and Mayo (1982) and a resolution of this controversy has been made whereby Wilkinson et al., 1983 developed the method of nearest neighbour (NN) analysis. This area of nearest neighbour model or in NN analysis in Wilkinson et al., would be most useful if it is applied to the analysis of experiments with those systematic designs (Mead in the discussion of Bartlett, 1978). Though the NN analysis shows, on average, much improved efficiency compared with the conventional analysis of variance, it is meant for sole crop experiments and has not been applied to intercropping systems yet. Hence, in intercropping it will still be worthwhile for an experimenter to seek the most effective form of blocking, to reduce the within block variation (Patterson and Ross, 1963; Pearce, 1978, 1980; Mead in the discussion of Bartlett, 1978). This will involve identifying the major blocking pattern of the given experimental area and choosing a suitable allocation of treatments to blocks (Mead in the discussion of Bartlett, 1978). It is true that variation will be continuous and blocks are discontinuous, but again no model is going to be perfect (Pearce, 1983).

As mentioned in Chapter V, experiments repeated both in sites and seasons are necessary to get the better cropping combination results. Hence, the proper organization of the storage of data is vital, so that cropping system × environment interactions can be assessed from records of many seasons and sites.

For Indonesian conditions the importance of uniformity trials for subsequent experiments should be re-emphasized, as the variations in fertility over the area are detected and the errors caused by soil fertility may also be estimated from the uniformity trial (Sanders, 1930). A limited number of such trials would aid in choosing the size and shape of plots, border rows, sampling methods, blockings and number of replications and also the appropriate experimental designs for the subsequent experiment. Such experiments would also provide base data for the evaluation of mixed cropping analogues of the NN designs and analyses mentioned already; additional field information can be vital in improving precision (Mead and Stern, 1980). Again, we should also re-emphasize the importance of the link of experimenters and statisticians or biometricians.

TABLE 7.1 The summary of the type of Indonesian intercropping experiments.

	% of experiment[a)]
The staple food intercrops	
Non legumes + legumes	64
- soybean	25
- peanut	30
- others	9
Non legumes + non legumes	36
The sugar-cane intercrops	
Sugar-cane + legumes	48
+ non legumes	52

a) The experiments that involve more than one in the 2nd crop are considered as more than one experiment depending on the number of the 2nd crop involved.

TABLE 7.2 The summary of type of intercrop, treatments or test factors, number of treatments and replications and experimental design for Indonesian intercropping experiments.

No. of Expts.	Intercrop	Test Factors	Number of Treat- ments	Number of Repli- cations	Design
1	Cassava + peanut	Peanut densities	4	6	Randomized Complete Block
33	" "	Nitrogen on cassava Nitrogen on peanut	12	3	Split Plot
2	Cassava + 2nd crops+)	Intercrop densities	6	4	" " "
3	Cassava + 2nd crops+	Type of second crops Second crop densities	9	3	" " "
4	Cassava + 2nd crops+	Type of second crops Second crop densities	9	3	" " "
5	Cassava + upland rice	Planting date of cassava	4	6	Randomized Complete Block
6	Maize + peanut	Nitrogen on maize Maize densities	6	3	Randomized Complete Block
7	" "	Nitrogen on maize	12	4	" " "
15	" "	Maize densities Planting distance of maize	8	3	" " "
16	" "	Peanut densities	12	3	" " "
17	" "	Planting date of maize + peanut	10	3	" " "
18	" "	Planting date of maize Maize densities	9	4	" " "
19	" "	Maize genotypes Maize densities	8	3	" " "
20	" "	Maize genotypes Maize densities	12	3	" " "
25	" "	Peanut genotypes	10	3	" " "
9	Maize + soybean	Planting systems Soybean genotypes	14	3	Split Plot
10	" "	Rows planting direction Within row distance of maize	12	3	Randomized Complete Block
11	" "	Rows planting direction Within row distance of maize	12	3	" " "
12	" "	Maize genotypes Soybean genotypes	12	3	" " "
22	Maize + soybean	Planting systems Maize genotypes Leaf cutting of maize	16	3	Split Plot

TABLE 7.2 cont'd.

No. of Expts.	Intercrop	Test Factors	Number of Treat-ments	Number of Repli-cations	Design
23	" "	Planting systems Maize genotypes Leaf cutting of maize	16	3	" "
29	" "	Soybean genotypes	11	3	Randomized Complete Block
31	" "	Maize genotypes Maize densities	12	3	" " "
32	" "	Nitrogen on maize	7	3	" " "
21	Maize + 2nd crops+	Type of second crop Insecticide treatments	8	3	" " "
8	Maize + mungbean	Planting systems Mungbean genotypes	14	3	Split Plot
13	" "	Maize genotypes Mungbean genotypes	12	3	Randomized Complete Block
14	" "	Maize genotypes Mungbean genotypes	12	3	" " "
24	Maize + upland rice	Planting systems Maize genotypes Leaf cutting of maize	18	3	Split Plot
26	" "	Upland rice genotypes	10	3	" " "
27	" "	Upland rice genotypes	10	3	" " "
28	" "	Upland rice genotypes	10	3	" " "
30	" "	Management methods Upland rice genotypes	20	3	Split Plot
36	" "	Leaf cutting of maize Maize genotypes Planting distance of maize	30	3	" "
37	" "	Between row distance of maize Leaf cutting of maize	15	3	Randomized Complete Block
38	" "	Between row distance of maize Leaf cutting of maize	15	3	" " "
34	Maize + sweet potatoes	Maize genotypes Planting system of maize Fertilizer treatments	24	3	Split Plot
35	" "	Maize genotypes Nitrogen on sweet potatoes Planting system of maize	24	3	" "
41	Sugar-cane + maize	Sugar-cane genotypes Maize genotypes	4	4	Randomized Complete Block

TABLE 7.2 cont'd.

No. of Expts.	Intercrop	Test Factors	Number of Treat-ments	Number of Repli-cations	Design		
42	" "	Sugar-cane genotypes Planting distance of maize	6	4	"	"	"
43	" "	Sugar-cane genotypes Between row distance of sugar-cane	6	4	"	"	"
44	" "	Between row distance of sugar-cane Planting systems	6	4	"	"	"
50	" "	Nitrogen on sugar-cane + maize	4	6	"	"	"
51	" "	Nitrogen on sugar-cane + maize	4	6	"	"	"
39	Sugar-cane + onion	Sugar-cane genotypes Within row distance of onion	4	4	"	"	"
40	Sugar-cane + tomatoes	Sugar-cane genotypes Within row distance of tomatoes	4	4	"	"	"
45	Sugar-cane + 2nd crops+	Type of second crops	2	7	"	"	"
46	" "	Type of second crops	2	7	"	"	"
47	" "	Type of second crops	4	6	"	"	"
48	" "	Type of second crops	4	6	"	"	"
49	" "	Type of second crops	6	4	"	"	"

+) Look at Section III.2 for details

-) Excluding sole crops if its function as a control rather than treatments

TABLE 7.3 The summary of plot size and coefficient of variation (CV) of Indonesian intercropping experiments.

Plot size	No. of Expt.	Intercrop	Coefficient of Variation (%) each crop analysis 1st crop	2nd crop	1st crop yield equivalence
18 × 12 m²	2	Cassava + 2nd crops+)	27.40	-)	10.70
	3	Cassava + 2nd crops+	17.40	-	7.80
12 × 7.5 m²	5	Cassava + upland rice	18.08	10.87	15.50
8 × 7.5 m²	4	Cassava + 2nd crops+	10.20	-	8.00
12 × 4 m²	1	Cassava + peanut	10.19	26.22	8.50
8 × 3 m²	33	Cassava + peanut	13.59	19.41	8.20
9 × 4.5 m²	21	Maize + 2nd crops+	13.30	-	13.80
8 × 6 m²	6	Maize + peanut	17.83	10.40	8.00
	17	Maize + peanut	5.56	4.61	3.70
	26a)	Maize + upland rice	19.46	19.88	14.70
	27a	Maize + upland rice	31.71	34.36	26.10
	28a	Maize + upland rice	44.98	16.97	19.40
8 × 4.5 m²	37b)	Maize + upland rice	15.61	24.38	15.30
	38b	Maize + upland rice	30.54	20.95	15.80
8 × 4 m²	25	Maize + soybean	26.40	16.06	15.80
8 × 3 m²	24	Maize + upland rice	13.60	22.20	8.50
	31	Maize + soybean	22.38	14.78	11.70
8 × 2.5 m²	12	Maize + soybean	21.41	18.14	12.60
	13c)	Maize + mungbean	13.77	12.57	6.70
	14c	Maize + mungbean	13.77	19.72	12.40
7 × 6.8 m²	9	Maize + soybean	15.00	14.30	13.40
7.2 × 4 m²	22d)	Maize + soybean	7.60	26.80	9.90
	23d	Maize + soybean	12.00	12.20	10.60
7 × 4 m²	8	Maize + mungbean	16.70	3.60	7.30
7 × 3 m²	36	Maize + upland rice	20.22	28.74	21.90
6.8 × 4.8 m²	10e)	Maize + soybean	11.50	30.39	3.32
	11e	Maize + soybean	15.87	18.14	15.00
6.7 × 6 m²	32	Maize + soybean	14.26	15.12	7.70
6 × 5 m²	7	Maize + peanut	14.86	2.99	4.70
	15	Maize + peanut	18.14	28.23	14.70
	16	Maize + peanut	10.20	14.00	10.90
6 × 4 m²	29	Maize + soybean	32.77	36.73	27.80
	30	Maize + upland rice	22.74	16.73	6.90
5 × 4 m²	34	Maize + sweet potatoes	55.60	14.58	12.70
	35	Maize + sweet potatoes	36.99	30.00	23.80
5 × 3.2 m²	19	Maize + peanut	6.22	4.64	4.50
5 × 2 m²	18	Maize + peanut	11.40	10.20	9.70
	20	Maize + peanut	10.67	29.06	12.90
50 × 10 m²	45	Sugar-cane + 2nd crops+	6.05	-	6.10
	46	Sugar-cane + 2nd crops+	6.00	-	3.90
20 × 12 m²	49	Sugar-cane + 2nd crops+	6.70	-	5.00
11 × 7.5 m²	50f)	Sugar-cane + maize	8.00	27.80	7.80
	51f	Sugar-cane + maize	4.80	22.60	3.30
10 × 7 m²	39	Sugar-cane + onion	6.12	36.83	6.90
	40	Sugar-cane + tomatoes	11.35	4.44	9.90
	41	Sugar-cane + maize	4.80	10.16	4.70
	42	Sugar-cane + maize	18.49	12.72	17.30
10 × 6 m²	44	Sugar-cane + maize	19.10	17.10	17.90
10 × 5 m²	47	Sugar-cane + 2nd crops+	3.50	-	5.50
8 × 6 m²	43	Sugar-cane + maize	5.46	-	5.30
7.5 × 6 m²	48	Sugar-cane + 2nd crops+	4.20	-	3.60

+) Look at Section III.2 for details

a = the same experiment different in sites

b = the same experiment different in seasons

c = the same experiment different in seasons

d = the same experiment different in sites

e = the same experiment different in season

f = the same experiment different in sites

TABLE 7.4 The coefficient of variation (CV) without blocking and the reduction of CV (%) due to block for each crop analysis.

No. of Expt.		CV (%) without blocking 1st crop	CV (%) without blocking 2nd crop	The Reduction of CV (%) due to block[a)] 1st crop	The Reduction of CV (%) due to block[a)] 2nd crop
1	Cassava + peanut	14.10	27.11	38	3
33	" "	17.11	20.42	26	5
2	Cassava + 2nd crops+)	27.16	-)	-11	-
3	Cassava + 2nd crops+	18.19	-	5	-
4	Cassava + 2nd crops+	10.20	-	0	-
5	Cassava + upland rice	18.53	-	2	27
6	Maize + peanut	14.91	10.07	-16	-3
7	" "	14.99	3.15	1	5
15	" "	17.65	27.60	-3	-2
16	" "	10.36	14.16	2	1
17	" "	6.28	8.26	13	79
18	" "	11.60	10.82	2	6
19	" "	6.57	11.71	6	152
20	" "	10.94	33.35	3	15
25	" "	27.23	18.11	3	13
9	Maize + soybean	29.78	26.02	99	82
10	" "	11.87	30.64	3	1
11	" "	16.31	18.38	3	1
12	" "	24.53	25.25	15	18
22	" "	10.39	35.37	37	32
23	" "	13.84	14.29	15	17
29	" "	34.03	40.96	7	12
31	" "	22.66	15.46	1	5
32	" "	18.76	23.62	32	56
21	Maize + 2nd crops+	12.12	-	-9	-
8	Maize + mungbean	19.26	11.47	15	219
13	" "	14.55	13.66	6	8
14	" "	13.90	21.79	1	10
24	Maize + upland rice	13.52	19.43	-1	-12
26	" "	21.45	19.99	10	1
27	" "	40.89	35.99	29	5
28	" "	48.42	18.17	8	7
30	" "	24.07	17.05	6	2
36	" "	42.52	49.44	110	72
37	" "	16.86	30.69	8	97
38	" "	49.94	32.96	64	8
34	Maize + sweet potatoes	57.15	23.64	3	62
35	" "	38.19	33.30	3	11
41	Sugar-cane + maize	4.96	11.74	3	16
42	" "	20.55	13.59	11	7
43	" "	16.90	4.99	210	77
44	" "	20.61	26.46	8	55
50	" "	7.19	26.56	-10	-4
51	" "	4.27	21.69	-11	-4
39	Sugar-cane + onion	5.51	32.59	-10	-12
40	Sugar-cane + tomatoes	12.11	5.48	7	23
45	Sugar-cane + 2nd crops+	8.79	-	45	-
46	Sugar-cane + 2nd crops+	6.82	-	14	-
47	Sugar-cane + 2nd crops+	5.22	-	49	-
48	Sugar-cane + 2nd crops+	8.19	-	95	-
49	Sugar-cane + 2nd crops+	6.61	-	-1	-

+) look at Section III.2 for details

-) involves more than one crop on secondary crops

a) it is calculated as $\frac{\text{CV(\%) without blocking}}{\text{CV(\%) with blocking}} - 100\%$

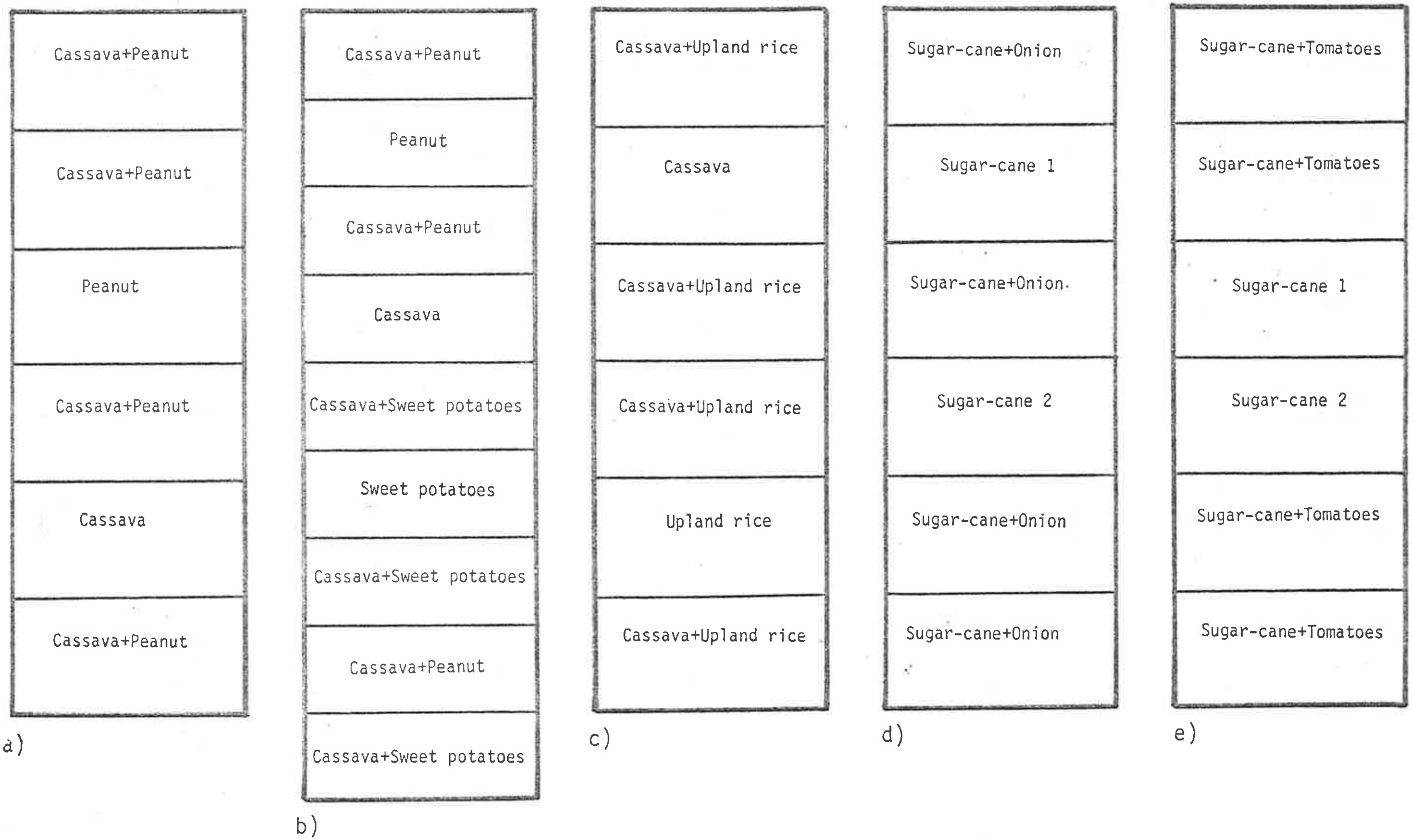

Fig.7.1 The randomization scheme of sole crops that are regarded as controls within intercrop treatments for one block of a,b,c,d and e are experiments 1,2,5,39 and 40 respectivelly.

VIII. GENERAL CONCLUSIONS

This thesis is concerned with the application of biometry to the real problems of agriculture in Indonesia rather than with the development of the statistical theory of intercropping experiments. The obvious problems in developing countries such as Indonesia appear to be the small numbers of statisticians and biometricians available. It has been suggested that the presence of trained statisticians or biometricians in developing countries is a luxury (Gomez, 1983). There will thus be few persons who can relate to the experimenters in using statistical techniques and at the same time be up to date in the development of relevant statistics. Gomez (1983) suggested that the solution should be cooperation with statisticians or biometricians in developed countries. They would develop the new methods and supply them to their colleagues in the developing countries who are strategically located to apply the methods and identify the problems that require the new methods.

I have been concerned to achieve the clear and unambiguous assessment of the results of intercropping experiments. I have dealt with the simple forms of Indonesian intercropping experiments where only two crops are involved. The study is also concentrated mainly on intercropping experiments involving staple food crops rather than sugar-cane. The fact that experimenters also tend to be interested in comparing different intercrop treatments has been an important reason for concentrating on such comparisons, though in some cases, we also examine sole crops versus intercrops.

The biometrical techniques used here have been developed to investigate three important aspects of interest in intercropping experiments. Firstly, Chapter IV covers the assessment of yield advantages in intercropping systems by different methods and testing the validity of these methods. The second aspect of interest is concerned in Chapter V: the cropping system × environment interaction and yield stability in intercropping experiments. The third one is the nature of competition analysis for intercropping experiments, presented in Chapter VI. Chapter VII, dealing with experimental design consideration for Indonesian intercropping experiments, provides an approach to guide lines for designing future experiments.

Section IV.1.1 and IV.1.2 dealt with the assumption underlying of the two popular methods (i.e. LER and bivariate analysis) for intercropping experiments. Both the distribution and the homogeneity of variance of LERs are quite satisfactory as long as there are no outliers in the data. The assumption of constant correlation for all treatments in the bivariate analysis is not always correct, so that this hypothesis needs to be tested as well as those relating to properties of treatment means.

In Section IV.2, I dealt with the assessment of yield advantages in intercropping systems by using a range of univariate and multivariate analyses: the analyses of each crop separately, the LERs, economic analysis as the first crop yield equivalence, multivariate analysis and bivariate analysis. The weaknesses and some enhancement of these methods are also discussed. The obvious difficulty concerning the assessment of yield advantages in intercropping systems is that there are two characteristics of interest (i.e. the two separate crop yields). Without determining the criterion of "the best", the problems of choosing the best treatment will not be solved. One possibility is to say that the higher first crop yield and second crop yield are preferable to smaller as is assumed in the LERs analysis. As a result in the LER analysis, the highest LER sometimes does not mean anything to the farmer as his requirement of staple food is not fulfilled by that crop combination. A graphical method of bivariate axes clearly displays the magnitude of the crop yields or the component LERs. The method, however, as in the multivariate analysis, suffers from the difficulty of estimation of treatment means.

The study offers a slightly different criterion of the best treatment and develops the model as the new effective LER (i.e. LER'). The best treatment is defined as that which has the yield of the main crop meeting the farmer's requirements and which also has the highest biological efficiency in terms of the LER'. The argument of the LER' as against the monetary value is that the monetary value analysis will change with the market situation. The study has shown that the highest treatment of the first crop yield equivalence at harvest time could be the lowest one in another season or year, given actual Indonesian price fluctuations. These will be rendered much worse by any bandwagon effect, i.e. everyone producing the same crop at the same time while simultaneously requiring the other crop also. Again, the study emphasizes the usefulness of considering LERs, the magnitude of component LERs or crop yields under bivariate analyses and the LER' together in order to interpret the yield advantages of intercropping experiments.

Chapter V dealt with the cropping systems × environments interaction and yield stability of intercropping systems. The study emphasized that though this area is one of the most important for intercropping in practice, there are few relevant experiments. The interesting result from the study is that the best genotypes under sole crops are not always the best either under intercrop situations. Hence, of varieties selection for intercropping systems should be carried out under intercropping, where practicable. The regression analysis and bivariate analysis would provide a comprehensive analysis for interpretation of the stability of yields in intercropping. The methods would be more appropriate if the experimenters realize the main goal of intercropping experiments. As emphasized earlier, the important task is to assess the best combination of crops and not to compare between sole crop versus intercrop. Hence, the determination of yield stability should also be concentrated on intercrop treatments. Given the limited number of repeated experiments, our study has also been limited, but the results have the merit of merging the study of cropping systems and environment interaction.

In Chapter VI, competition analyses for intercropping systems are presented. The bivariate graphical method shows that as they do not distinguish the degree of yield advantage, the previous competition functions are largely uninformative. By using the bivariate graphical analysis, the two main results are already apparent. First, there is the highly informative display of the magnitude of the two crop yields and the yield advantages in terms of the contour line of equal LERs (as presented in Section IV.2). The second one is the determination of which crop yield is dominant or dominated. The final yields or combined yields in intercropping are the most important criterion, but the yields themselves usually do not add anything to our knowledge of how these yields arose and should best be achieved. The study emphasized the obvious importance of a knowledge of growth and the other characters of crops in determining the final yields. Again, the study demonstrates the usefulness of bivariate graphical display, not only in detecting the degree of dominance of the two crop yields, but also for determining the other traits that are likely to be important in determining competition between two crops, whether through nutrient uptake, light interception or whatever.

While the preliminary or exploratory intercropping research continues, little attention has been paid to experimental design principles; a first attempt at this appears in Chapter VII. In some cases, the experimenters are not consistent in meeting the objectives of experiments through appropriate field experimental design. For example, sole crops are regarded as controls, but included in the randomization process within the main treatments (i.e. intercrop treatments) as well. Design criteria suggest that intercropping experiments should have at least twice as many treatments as sole crops, but in general the experiments only involve a small number of treatments. This emphasizes the need for more work on design. It has also been emphasized that intercropping experiments are too large to be handled efficiently as single stage experiments. Hence, it is important to have factorial structure at first stage with many factors, but few levels in order to identify the presence of interactions among the factors. In the second stage, one would differentiate between factors that show interaction and those which do not. For the factors that show no interaction, single factor experiments can be done, or incorporated simply into larger experiments, whereas those with large interactions should be carried out with fewer factors but more levels for each factors. Again this shows the importance of exploring the principles of experimental designs as much as possible in order to achieve better intercropping experiments. From this study, it also appears that border rows, size and shape of plots, sampling methods, numbers of replications and method of blocking for Indonesian intercropping experiments require further thought and research. The neglect of uniformity trials under Indonesian conditions certainly may disturb the results of subsequent experiments or waste experimental material. Cooperation between statisticians or biometricians and experimenters is vital in using the advanced statistical techniques in order to get the better result of Indonesian intercropping experiments.

In final conclusion of this thesis, I would like to re-emphasize that in Indonesia, as in other developing countries, the unsolved problems of design and analysis of intercropping experiments are still many, but I believe I have demonstrated the utility of existing statistical techniques for practical intercropping experiments in Indonesia and highlighted what needs to be done next.

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APPENDICES

APPENDIX A.1

A FORTRAN program for simulating mixed cropping experiments

```
      PROGRAM PIGEON(INPUT,OUTPUT)
      DIMENSION V(2000)
      DIMENSION PLOTP(3,5,7),PLOTS(3,5,7),ITREAT(3,5,7)
      DIMENSION PVAR(2,17),SVAR(17),ITEST(35)
      DOUBLE PRECISION DSEED
      IRAN=0.0
      DO 20 I=1,17
   20 READ 26,PVAR(1,I),PVAR(2,I),SVAR(I)
   26 FORMAT(3F6.0)
      SSAR=7000.0
      PPVAR=170.0
      PSVAR=140.0
      SPVAR=260.0
      SSVAR=370.0
      DSEED=31859.D0
      NORM=2000
      CALL GGNML(DSEED,NORM,V)
C
C     THIS PROGRAM SETS UP AN EXPERIMENT WITH 3 COMPLETE
C     BLOCKS WITH 35 TREATMENTS RANDOMISED IN EACH.
C     TREATMENT 1 IS SOLE SORGHUM, TREATMENTS 2 TO 18
C     ARE 17 VARIETIES OF PIGEON-PEA GROWN WITH SORGHUM,
C     AND TREATMENTS 19 TO 35 ARE THE SEVENTEEN VARIETIES
C     OF PIGEON-PEA GROWN BY THEMSELVES. VALUES ARE TAKEN
C     FROM MEAD AND RILEY (1981).
C     PVAR AND SVAR ARE MEAN YIELDS GIVEN ON P. 467
C     OF MEAD AND RILEY.  PPVAR, PSVAR AND SPVAR ARE
C     THE STANDARD DEVIATIONS OF THE TABULATED SETS
C     OF MEANS.
C     ITREAT IS THE PIGEON-PEA-SORGHUM COMBINATION
C     APPLIED TO EACH PLOT AND PLOTP AND PLOTS ARE
C     THE YIELDS OF PIGEON-PEA AND SORGHUM RESPECTIVELY
C     FROM EACH PLOT.
C
      DO 80 I=1,3
      DO 40 ID=1,35
   40 ITEST(ID)=0
      DO 70 J=1,5
      DO 70 K=1,7
   50 X=RANF(0)
      IMP=35.0*X+1.0
      IF(ITEST(IMP).EQ.1)GO TO 50
      DO 60 IA=1,35
      IF(IMP.EQ.IA)ITEST(IA)=1
   60 CONTINUE
      ITREAT(I,J,K)=IMP
   70 CONTINUE
   80 CONTINUE
      DO 120 I=1,3
      DO 120 J=1,5
      DO 120 K=1,7
C     THIS SET OF LOOPS ESTABLISHES THE VARIETAL
C     ELEMENT OF THE PLOT YIELDS.
      PLOTP(I,J,K)=0.0
      PLOTS(I,J,K)=0.0
      ISET=ITREAT(I,J,K)
      IF(ISET.NE.1)GO TO 90
      IRAN=IRAN+1
      PLOTS(I,J,K)=SSAR+SSVAR*V(IRAN)
      GO TO 120
   90 IF(ISET.LT.2.OR.ISET.GT.18)GO TO 100
      IRAN=IRAN+1
      PLOTP(I,J,K)=PVAR(2,ISET-1)+PSVAR*V(IRAN)
      IRAN=IRAN+1
      PLOTS(I,J,K)=SVAR(ISET-1)+SPVAR*V(IRAN)
      GO TO 120
  100 IF(ISET.LE.18)GO TO 120
      IRAN=IRAN+1
      PLOTP(I,J,K)=PVAR(1,ISET-18)+V(IRAN)*PPVAR
  120 CONTINUE
      DO 180 I=1,3
      DO 180 J=1,5
      DO 180 K=1,7
      IF(PLOTP(I,J,K).EQ.0.0)GO TO 140
      IF(PLOTS(I,J,K).EQ.0.0)GO TO 160
C     THIS SET OF LOOPS ADDS A RANDOM ELEMENT TO THE
C     YIELD OF EACH PLOT.
```

```
      IRAN=IRAN+1
      PLOTP(I,J,K)=PLOTP(I,J,K)+PSVAR*V(IRAN)
      IRAN=IRAN+1
      PLOTS(I,J,K)=PLOTS(I,J,K)+SPVAR*V(IRAN)
      GO TO 180
  140 IRAN=IRAN+1
      PLOTS(I,J,K)=PLOTS(I,J,K)+SSVAR*V(IRAN)
      GO TO 180
  160 IRAN=IRAN+1
      PLOTP(I,J,K)=PLOTP(I,J,K)+PPVAR*V(IRAN)
  180 CONTINUE
C     THIS SET OF LOOPS PRINTS OUT THE LAYOUT
C     AND THE PLOT YIELDS.
      DO 220 I=1,3
      DO 200 J=1,5
      PRINT 260,((ITREAT(I,J,K),K),K=1,7)
      PRINT 280,(PLOTP(I,J,K),K=1,7)
      PRINT 280,(PLOTS(I,J,K),K=1,7)
  200 CONTINUE
  220 CONTINUE
  260 FORMAT(1X,14I7)
  280 FORMAT(1X,7G14.7)
      STOP
      END
```

APPENDIX A.2

A GENSTAT program for applying an analysis of variance to each crop yield and the Land Equivalent Ratio (LER). Also a multivariate and bivariate analysis of variance of the two crop yields is given.

This program is modified from MANOVA GENSTAT macros and it is applied to experiment 18.

```
WYWAEGU,T40,CM140000.          BOX 133 WAITE                                          WAEGO
ATTACH,GENSTAT,ID=U.
GENSTAT.

"REFE/NUNN=200,NID=200" EXPT18
"MACRO" MANOVA $
"LOCA" V,VECTS,ROOTS,TRCE,LAB,KLIM,H3 ,J,KK,DUM,OUTPUT,I,K,H4,
L,H1,H2,HSSP,ESSP,DETESSP,DETHESSP,WILKSLAM,PILLBART,ROYSTEST
 ,L2,L3,DFE,DFH
 "SCAL" L2,L3,DFH(1...NT),DFE(1...NB)
 "HEAD" H1="" **** TREATMENT TERM""  : H2="" ****""
 "HEAD" H3=""***** ERROR STRATUM"" : H4="" *****""
 "COVA" VARIATES
 "POIN" V=VARIATES
 "MATR" VECTS $ V,V
 "DIAG" ROOTS $ V
 "SYMM" ERRSSPS,HYPSSPS $ V
 "SCAL" J,K,KLIM,TRCE,LAB
 "ASSI" KK=VARIATES $ 1
 "VARI" DUM $ KK
 "CALC" DUM=1
 "BLOC" BLOCKS
 "TREA" TREATS
 "ANOV/PRX=PRX,PRYU=-1,PR=-1,LINA=LINA" DUM;OUT=OUTPUT
 "EXTR" OUTPUT;BLOCKS $ SSPM= ERRSSPS;DF =DFE(1...NB)
 "CALC" DFE(1...NB)=DFE(1...NB)+NVAL(V)
 "SCAL" DETESSP,DETHESSP    ,WILKSLAM,PILLBART,ROYSTEST
 "FOR" I=1...NB;ESSP=ERRSSPS;DFE=DFE(1...NB)
 "PAGE"
 "PRIN/C,VAR=1,LABR=1" H3,I,H4 $ 2.0
 "CAPT" ""
        ** ERROR SSP-MATRIX, ESSP ** ""
 "PRIN" ESSP $ 10.4
 "CALC" DETESSP=DET(ESSP)
 "JUMP" L2*(DETESSP.EQ.0)
 "CAPT" ""
        * DEGREES OF FREEDOM *""
 "PRIN" DFE $ 5.0
 "LINE" 3
 "JUMP" L3
 "LABE" L2
 "CAPT" "" ERROR SSP-MATRIX IS SINGULAR
  NO TESTS IN THIS ERROR STRATUM ""
 "LABE" L3
 "CALC" J=-I
 "CALC" KLIM=TRACE(ESSP)*0.00001
 "EXTR/STRA=J" OUTPUT;TREATS $ SSPM= HYPSSPS;DF =DFH(1...NT)
 "FOR" HSSP=HYPSSPS;L=1...NT;DFH=DFH(1...NT)
 "CALC" K=TRACE(HSSP)
 "JUMP" LAB*((K.LT.KLIM).OR.(K.EQ.0))
 "LINE" 10
 "PRIN/C,VAR=1,LABR=1" H1,L,H2 $ 3.0
 "CAPT"  ""
        ** HYPOTHESIS SSP-MATRIX, HSSP **""
 "PRIN" HSSP $ 10.4
 "CAPT" ""
        * DEGREES OF FREEDOM *""
 "PRIN" DFH $ 5.0
 "JUMP" LAB*(DETESSP.EQ.0)
 "CALC" DETHESSP=DET(HSSP+ESSP)
 "LINE" 3
 "CALC" WILKSLAM=DETESSP/DETHESSP
 "CAPT"  ""
        ** WILK'S LAMBDA CRITERION,  DET(ESSP)/DET(HSSP+ESSP) **  ""

 "PRIN" WILKSLAM     $ 10.4
 "CAPT"  ""
        ** PILLAI-BARTLETT TRACE,  TRACE(HSSP*INV(HSSP+ESSP)) **""

 "CALC" PILLBART=TRACE(PDT(HSSP;INV(HSSP+ESSP)))
 "PRIN" PILLBART $ 10.4
 "LRV"HSSP,ESSP;VECTS,ROOTS,TRCE
 "CAPT"  ""
        ** ROY'S MAXIMUM ROOT TEST, MAXROOT/(1+MAXROOT) **      ""

 "EQUA" ROYSTEST=ROOTS
 "CALC" ROYSTEST=ROYSTEST/(1+ROYSTEST)
 "PRIN" ROYSTEST $ 10.4
 "CAPT"   ""
        ** LAWLEY-HOTELLING TRACE, TRACE(HSSP*INV(ESSP)) ** ""
 "PRIN"  TRCE $ 10.4
 "LINE" 3
 "CAPT" ""
        ** CANONICAL VARIATES OF INV(ESSP)*HSSP : ROOTS,LOADINGS ** ""
```

```
"CAPT" ""
                 ROOTS ""
"PRIN/LHN=13,LABC=1" ROOTS $ 10.4
"CAPT" ""
                 LOADINGS ""
"PRIN/S,LABC=1"         VECTS       $ 10.4
"LABE" LAB
"REPE"
"REPE"
"DEVA" VECTS,DUM,ROOTS
"ENDMACRO"


"PRINT" MANOVA
"SCALAR" N=4 ,NLA=3 ,NLB=3 ,SX1=2.363 ,SX2=9.7546 :M,NM
"CALC" M=NLA*NLB :NM=N*M
"RUN"
"UNIT" $ NM
"FACT" BLOCK $N :A $NLA ,B $NLB ,PLOT $M
"GENERATE" PLOT,BLOCK
          : A,B,M
"SET"VARIATES=X,Y
"READ/P"X,Y
"CALC" X1=X :X2=Y
"SET/M" BLOCKS=BLOCK+BLOCK.PLOT
"SET/M" TREATS=A*B
"SCAL" NB=2 : NT=3
"SET" ERRSSPS=SSPRESID (1...NB)
"SET" HYPSSPS=SSP(1...NT)
"SCAL" LINA=3 : PRX=10
"PAGE"
"CAPT" ""MULTIVARIATE ANALYSIS OF VARIANCE""
"USE" MANOVA $
"PAGE"
"CAPT" ""BIVARIATE ANALYSIS OF VARIANCE AS IT WAS DESCRIBED IN II.1""
"MACRO" PLT $
"VARI" B1(1...M), B2(1...M) ,A1(1...M),A2(1...M) $N
"EQUATE" B1(1...M)=Y1 ,B2(1...M)=Y2 :A1(1...M)=Z1 :A2(1...M)=Z2
"SCAL" V1(1...M) ,V2(1...M) ,W1(1...M) :W2(1...M)
"CALC" V1(1...M)=MEAN(B1(1...M)) :V2(1...M)=MEAN(B2(1...M))
      ,W1(1...M)=MEAN(A1(1...M)) :W2(1...M)=MEAN(A2(1...M))
"VARI" Y1BAR,Y2BAR ,Z1BAR,Z2BAR $M
"EQUATE" Y1BAR=V1(1...M) ,Y2BAR=V2(1...M)
        ,Z1BAR=W1(1...M)  ,Z2BAR=W2(1...M)
"HEADING" HY1=""Y1"" ,HY2=""Y2""
"GRAPH/ATX=HY1,ATY=HY2" Y2BAR;Y1BAR
"PRINT/P" Y1BAR,Y2BAR,Z1BAR,Z2BAR $4(10.5)
"ENDMAC"
"PRINT" PLT $
"SCAL" BAB,BA,BB, FAB,FA,C0,C1,C2,TAB1,TAB12,TAB2,TA1,TA12,TA2,TB1,TB12
      ,TB2,FB,V11,V22,DTAB,DTA,DTB,V1,V12,V2,SSA1,SSA12,SSA2
      ;SSB1,SSB12,SSB2,SSAB1,SSAB12,SSAB2,DE,DA,DB,DAB
"CALC" DE=DFE(NB), DA,DB,DAB=DFH(1...NT)
      : SSPRESID(NB)=SSPRESID(NB)/DE
"EQUATE" V1,V12,V2=SSPRESID(NB)
      , SSA1,SSA12,SSA2=SSP(1) ,SSB1,SSB12,SSB2=SSP(2)
      : SSAB1,SSAB12,SSAB2=SSP(3)
"CALC" V11=V1-V12**2/V2 :V22=V2-V12**2/V1
     ,C0=1/SQRT(V1) :C1=-V12/(V1*SQRT(V22)) :C2=1/SQRT(V22)
        ,Y1=X1/SQRT(V1) :Y2=(X2-V12*X1/V1)/SQRT(V22)
     ,Z1=X1/SQRT(V11) ,Z2=X2/SQRT(V22) :TAB1=SSAB1*C0*C0
     ;TAB12=SSAB1*C0*C1+SSAB12*C0*C2
     ;TAB2 =SSAB1*C1*C1+2*(SSAB12*C1*C2)+SSAB2*C2*C2
     ,TA1=SSA1*C0*C0 :TA2=SSA1*C1*C1+2*(SSA12*C1*C2)+SSA2*C2*C2
     ;TA12=SSA1*C0*C1+SSA12*C0*C2 ,TB1=SSB1*C0*C0
     ;TB12=SSB1*C0*C1+SSB12*C0*C2
     ;TB2=SSB1*C1*C1+2*(SSB12*C1*C2)+SSB2*C2*C2
     ;BAB=(TAB1+DE)*(TAB2+DE)-TAB12**2 :BA=(TA1+DE)*(TA2+DE)-TA12**2
     ,BB=(TB1+DE)*(TB2+DE)-TB12**2 :DTAB=DE**2/BAB: DTA=DE**2/BA:DTB=DE**2/BB
     ;FAB=(SQRT(BAB)-DE)*(DE-1)/(DAB*DE) :FA=(SQRT(BA)-DE)*(DE-1)/(DA*DE)
     ;FB=(SQRT(BB)-DE)*(DE-1)/(DB*DE)
"CALC" LER=X1/SX1+X2/SX2
"PRINT/P" A,B,BLOCK,X1,X2,Y1,Y2,Z1,Z2,LER $3(7),7(8.4)
         :FAB,FA,FB,V11,V22 $5(10.6)
"USE/R" PLT $
"CAPT" ""ANALYSIS OF VARIANCE ON LER AS IT WAS DESCRIBED IN II.1 ""
"TREAT" A*B
"BLOCK" BLOCK
"COVA"
"ANOVA" LER;FVAL=F;RES=R
"GRAPH" R;F
"RUN"
```

Factor statements

Declare:
- number of replication=N
- number of level A =NLA
- number of level B =NLB
- the yield of sole crop as SX_1 and SX_2

```
2.782 5.7229 3.184 6.0916 2.854 5.9958 2.644 5.9760
2.287 6.0404 1.800 5.7832 1.773 7.2062 2.255 6.3593
1.103 6.9166 1.540 6.2874 1.280 5.8992 1.358 7.9497
2.808 6.1960 2.937 5.1541 2.934 7.0541 2.354 6.2945
1.424 5.7566 2.129 7.6092 1.770 6.2365 1.890 5.8674
1.128 7.8374 1.277 7.1933 1.122 6.1931 1.271 6.1797
2.140 7.9643 2.281 7.7688 2.817 9.3087 2.343 8.1894
1.628 7.5057 1.752 9.2467 1.907 8.5402 1.964 7.7139
0.992 8.6499 1.099 9.2528 1.144 9.0562 1.020 8.9034
"EOD"
"CLOSE"
```

Put the data in order as in Factor statements.

APPENDIX B. 1

Models of Gene Effects for a Quantitative Trait in Man

published by

Mayo, O., Eckert, S.R. and Nugroho, W. H. (1982)

Mayo, O., Eckert, S. R. & Nugroho, W. H. (1982). Models of gene effects for a quantitative trait in man. In Malhotra, K. C. & Amitabha, B. (Eds.) *Proceedings of the Indian Statistical Institute Golden Jubilee Conference on Human Genetics and Adaption,* (Vol 1. pp. 479–489). Calcutta, Indian Statistical Institute.

APPENDIX B. 2

Properties of the Major Gene Index and Related Functions

published by

Mayo, O., Eckert, S.R. and Nugroho, W. H. (1983)

Mayo O., Eckert S. R. & Nugroho W. H. (1983). Properties of the major gene index and related functions. *Human Heredity*, *33*(4), 205–212.

APPENDIX C

A proof of the applicability of homogeneity variance test for residuals

The tests of homogeneity of variances also apply in the residuals after fitting the column or row effects separately as described below.

Suppose

$$X_{ij} = \mu + \alpha_i$$

where $\hat{\mu} = \bar{x}_{..}$

$$\hat{\alpha}_i = \bar{x}_{i.} - \bar{x}_{..}$$

The residual is

$$r_{ij} = X_{ij} - (\hat{\mu} + \hat{\alpha}_i)$$

$$= X_{ij} - \bar{x}_{i.}$$

Note that $\bar{r}_{i.} = 0$

So the estimate within variance of the residuals for group i is

$$\frac{1}{n_i - 1} \sum_{j=1}^{n_i} (r_{ij} - \bar{r}_{i.})^2 = \frac{1}{n_i - 1} \sum_{j=1}^{n_i} r_{ij}^2$$

$$= \frac{1}{n_i - 1} \sum_{j=1}^{n_i} (X_{ij} - \bar{x}_{i.})^2$$

$$= S_i^2 ,$$

the same as the estimated variance of the original data (X_{ij}).