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Intercropping—Its Importance and Research Needs. Part 1. Competition and Yield Advantages*

R. W. WILLEY**

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**International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), 1-11-256, Begumpet, Hyderabad 5000 16, A.P., India.

1. Introduction

Very recently, there has been a rapidly growing interest in intercropping as a potentially beneficial system of crop production. Yet many workers have found it difficult to initiate research programmes because of the complexity of the intercropping situation and the lack of information reaching world literature. Outside the field, little is known about what the advantages of intercropping really are, how they arise and how they might be improved; above all, it is not generally appreciated what the research priorities are and how they can be studied.

This review discusses the information currently available and tries to clarify some of the concepts and research objectives. It suggests criteria for determining advantages and ways of assessing these advantages quantitatively; it also reviews the evidence for advantages being due to better use of growth resources. Agronomic relationships are then discussed, with some special consideration of how the study of these could be further developed. Finally, a few brief comments are made on experimental designs and the simpler aspects of statistical analysis.

1.1. Terminology

Intercropping can be defined as the growing of two (or more) crops simultaneously on the same area of ground. The crops are not necessarily sown at exactly the same time and their harvest times may be quite different, but they are usually 'simultaneous' for a significant part of their growing periods. This distinguishes intercropping from 'relay' cropping in which growing periods only briefly overlap. It has been suggested that the term intercropping should also imply that the crops are grown in separate rows, and that any arrangement where there is irregular broadcasting or mixing within the row should be defined as 'mixed cropping' (Andrews and Kassam, 1975; Freyman and Venkateswarlu, 1977; Ruthenberg, 1971). This can be a useful distinction but is difficult to adhere to in a review of this kind where general reference is made both to research (very predominantly 'intercropping') and farming practice (very often 'mixed cropping'). Moreover, these two terms have often been used synonymously in the past. For simplification, therefore, in this review 'intercropping' is used in a general sense without implying any specific spatial arrangement. Similarly, unless specific reference is being made to more complex situations, it is assumed that only two crops are present.

'Component crop' is used to refer to either of the individual crops making up the intercropping situation. 'Intercrop yield' is the yield of a component crop when grown in intercropping and expressed over the total intercropped area (i.e. area occupied by both crops). A simple addition of both intercrop yields thus gives a 'combined intercrop yield'. 'Sole crop' refers to a component crop being grown alone and unless otherwise indicated is assumed to be grown at optimum population and spacing. 'Combined sole crop yield' is the combined yield achieved when unit area is divided between the two sole crops in some given proportion (see later). Unfortunately, in the highly relevant research area of plant competition, these terms are not always very satisfactory, mainly because the plants being considered are often not crop species. Thus, when referring to competition studies, more appropriate synonyms are used: in the order given above, these are 'mixture', 'component species', 'mixture yield', 'combined mixture yield', 'pure stand', and 'combined pure stand yield'.

1.2. Background

Intercropping has long been recognised as a very common practice throughout the developing tropics. In India, for example, its importance was highlighted almost 30 years ago in a very comprehensive review by Aiyer (1949). Historically, however, it has been regarded as a primitive practice 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 at least the foreseeable future (Arnon, 1972; Dalrymple, 1971; Francis *et al.*, 1975; Guttierrez *et al.*, 1975; Norman, 1974; Okigbo and Greenland, 1975).

It has also been realized that little improvement of the intercropping situation is likely to result from research which considers only sole crops, and there is a growing appreciation of the need for some research emphasis specifically on intercropping. The continuing importance of intercropping in farming practice would alone justify this emphasis, but an equally valid reason is the possibility that intercropping can provide yield advantages compared to sole cropping. Recent evidence suggests that these advantages can be very substantial; they may also be especially important because they are achieved not by means of costly inputs but by the simple expedient of growing crops together. One suggested form of advantage is greater stability of yield over different seasons. This is thought to be of particular importance to poorer subsistence farmers. Little work has been done on the stability aspect but the limited evidence available is discussed in Section 4.2. The other form of advantage, and one much more commonly examined, is the higher yields in a given season; this aspect constitutes the basis of this review and wherever general reference is made to yield advantages it is this form which is intended.

A major cause of yield advantages, and the only one for which there is much evidence to date, is the better use of growth resources. Thus this is the only one discussed in any detail later (see Section 4). However, other causes have been suggested. Perhaps the most important 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; Baker and Norman, 1975; Batra, 1962; Crookston and Kent, 1976; Finlay, 1974; International Rice Research Institute, 1972, 1975; Nickel, 1973; Pinchinat *et al.*, 1975; Raheja, 1977) and some of the possible mechanisms have been reviewed (Trenbath, 1975; Kayumbo, 1976; Litsinger and Moody, 1975). But there have also been instances of poorer control (ICRISAT unpublished data; Osiru, 1974; Pinchinat *et al.*, 1975) and it should be appreciated that intercropping is not necessarily advantageous in this respect. There are obviously some highly complex relationships involved and much more research is needed in this field. 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 (Rathke and Hegstrom, 1975), or a more continuous leaf cover may give better protection against erosion (Dennison, 1956; Siddoway and Bonnett, 1975).

It must also be appreciated that there can be some disadvantages of intercropping. These can take the form of a yield decrease because of adverse competitive effects (see Section 3.1. later); although such effects are likely to be rare. Allelopathic effects may also occur (Rice, 1974; Risser, 1969). 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 mechanisation or where the component crops have different requirements for fertilizers, herbicides, pesticides, etc. These difficulties are typically associated with more developed agriculture; the poorly developed farmer not only seems well able to handle intercropping but often seems to have a strong inherent preference for it. In this respect, it is worth emphasising that a further justification for more intercropping research is that it is the small farmer of limited means who is most likely to benefit.

2. Criteria for Assessing Yield Advantages

It is not always appreciated that different intercropping situations may have to satisfy rather different requirements if yield advantages are to be achieved. Yet it is important to recognise these different requirements, not just to ensure that advantages are validly assessed, but also to ensure that research aimed at improving the intercropping situation is based on sound objectives. Three different situations can be distinguished:

(i) *Where intercropping must give full yield of a 'main' crop and some yield of a second crop.* This situation is largely ignored in the literature, yet it is often applicable where the primary requirement is for a full yield of some staple food crop. It is an easily defined situation since, by definition, a yield advantage occurs if there is any yield of a second crop. But this situation illustrates how important it is to clarify research objectives, since the common research approach of examining widely different proportions of the component crops is quite inappropriate here. This has been well recognised in India where the primary objective of many intercropping combinations is to produce a full yield of a staple cereal. Much of the Indian intercropping work has therefore rightly been aimed at maximizing yield of the second crop without reducing yield of the main crop.

(ii) *Where the combined intercrop yield must exceed the higher sole crop yield.* This is the criterion which has traditionally been used for assessing yield advantages in grassland mixtures (van den Bergh, 1968; Donald, 1963), though it was also used by Trenbath (1974) for assessing a wider range of intercropping situations. It is based on the assumption that unit yield of each component crop is equally acceptable and therefore the requirement is simply for maximum yield regardless of the crop from which it comes. It must be appreciated, however, that this criterion also assumes that growing only the higher yielding sole crop is a valid alternative to growing both. Whilst this may be true for very similar crops, such as different grass species or different geneotypes within a species, it may not be so where rather different types of crops are grown (see (iii) below).

(iii) *Where the combined intercrop yield must exceed a combined sole crop yield.* This criterion is based on the assumption that a farmer usually needs to grow more than one crop, e.g. to satisfy dietary requirements, to spread labour peaks, to guard against market risks, etc. In this situation, a yield advantage occurs if intercropping gives higher yields than growing both the component crops separately; in fact, the combined intercrop yield does not now have to outyield the higher yielding sole crop, since by definition growing only the latter is not an acceptable alternative to growing both crops. This is much the commonest situation in practice and it is the one mainly considered in this review. Unfortunately, it is also a situation in which the magnitude, or even the existence, of a yield advantage is not readily apparent. Part of the problem is that component crops which are often very different in type, or level, of yield must be put on some comparable basis. A more difficult aspect is that any assessment of a yield advantage involves the comparison of an intercropping situation in which the component crops are competing with each other, with a sole crop situation in which they are not. Such a comparison must take into account the competitive relationships between crops. The next section discusses some of these relationships and examines how they can help to put the assessment of yield advantages on a valid, quantitative basis.

3. Competitive Relationships

3.1. *Competition and yield advantages*

Most competition studies have examined two species grown in a 'replacement series'. This is a series of treatments which contains the pure stands of each species and some mixture treatments formed by replacing given proportions of one species with equivalent proportions of the other.

The simplest replacement series, quite often studied, consists of two pure stands and a single mixture treatment (usually 50% of each species, i.e. 50:50). Competitive effects can be examined by the type of diagram illustrated in Fig. 1. This shows actual yields (unbroken lines) and 'expected' yields (broken lines) for each separate species and for the total of both species. 'Expected' yields are those that would be obtained if each species experienced the same degree of competition in mixture as in pure stand, i.e. if inter-specific competition was equal to intra-specific competition. This may be unlikely in practice, but provides a useful basis from which to describe different competitive situations.

Many such situations have been distinguished (Hart, 1974; Hill and Shimamoto, 1973; Trenbath, 1975; White, 1974) but for present purposes only three broad categories need be recognised. The first (Fig. 1a) is when the actual yield of each species is less than expected. This can be termed *mutual inhibition*: it is rare in practice but has been observed by some workers (Ahlgren and Aamodt, 1939; Donald, 1946; Harper, 1961). The second (Fig. 1b) is where the yield of each species is greater than expected. This can be termed *mutual cooperation* and is not unusual. The third, and much the commonest situation (Figs. 1c and 1f), is where one species yields less than expected and the other more; this can be termed *compensation*. In compensation situations the competitive abilities of the two species obviously differ. Many terms have been suggested to describe the more and less competitive species in a mixture; in this review the terms *dominant* and *dominated* as recently used by Huxley and Maingu (1978) are preferred.

It is evident that the mutual inhibition situation cannot give a yield advantage by mixing species, whereas the mutual cooperation situation must do so. But where compensation occurs, the possible advantage of mixing is not so clear. Consider now that the 'expected' yields in Fig. 1 are also those that would be obtained if unit area were divided into pure stands of the two species in the proportions indicated on the horizontal axis; the diagonals are thus the pure stand yields of each species and the uppermost broken line becomes a 'combined pure stand yield'. A vertical comparison between this combined pure stand yield and the combined mixture yield (top unbroken line) would now seem to give a simple assessment of any yield advantage of mixing; for example, on this basis the two mixtures illustrated in Fig. 1c and Fig. 1f both appear to show an advantage. Because of differences in competitive abilities, however, the combined mixture yield in such a comparison contains a bigger proportion of the dominant species than does the combined pure stand yield. Thus, if the dominant species is the higher yielding (usually but not necessarily so), this comparison is biased in favour of mixing; conversely, if the dominant species is the lower yielding, the comparison is biased in favour of pure stands.

Willey and Osiru (1972) avoided the above bias by calculating the proportions of sole cropping which

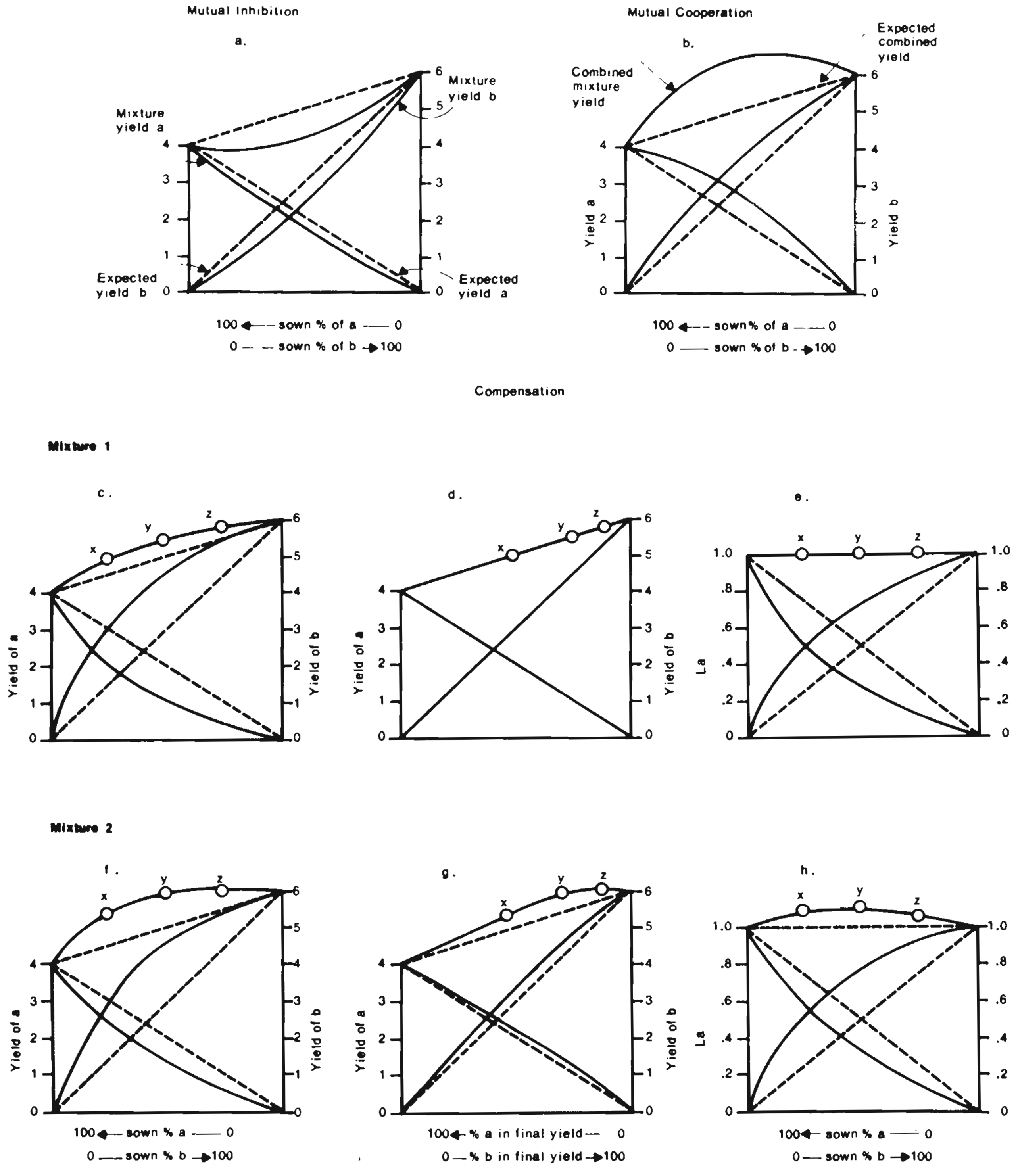

Figure 1. Types of inter-species competition.

would give the same final *yield* proportions as in intercropping. Thus in Mixture 2 (Figure 1f) the mixture yields at 50:50 combination were 1.32 units of a and 4.62 units of b. As pure stands, these yields would be achieved from 0.33 and 0.77 units of land area, respectively. On a proportional basis these are equal to 30% and 70%. Thus the combined mixture yield (5.94) is directly comparable with the combined pure stand yield at 30:70 proportion (1.20 of a + 4.20 of b = 5.40). The yield advantage for the mixture in this instance is therefore 10%. A similar calculation for Mixture 1 (Fig. 1c) shows that the 50:50 mixture must be compared with pure stands in a 25:75 proportion and that the combined mixture yield is then identical with the combined pure stand yield (5.50). In Mixture 1, therefore, there was no real advantage of mixing since the combined mixture yield could equally well have been obtained from the same total area of ground by appropriate division into pure stands. This procedure can be made simpler but this present form has suggested one way of illustrating replacement series data more meaningfully (White, 1974). In Figs. 1d and 1g the combined mixture yields are plotted against the appropriate pure stand proportions as calculated above. Vertical comparisons between combined yields are now valid, the yield advantage in Mixture 2 and the lack of advantage in Mixture 1 now becomes apparent.

More recently a rather simpler procedure, analogous to the first part of the above calculation, has become common practice in intercropping studies. This is the calculation of a Land Equivalent Ratio (LER). This may be defined as the relative land area under sole crops that is required to produce the yields achieved in intercropping: it is usually stipulated that the "level of management" must be the same for intercropping as for sole cropping, but see Section 5.1.1. later. The LER term is usually applied to combined intercrop yields but can be applied equally usefully to the intercrop yield of each crop. In this review, the latter use is denoted by L; L_a and L_b thus indicate the LERs for the intercrop yields of crop a and crop b, respectively. As an example of the calculations of LERs, it was seen that the 50:50 mixture yields of Mixture 2 (Fig. 1f) would have been produced from .77 and .33 units of land as pure stands. This means $L_a = 0.77$, $L_b = 0.33$ and LER = 1.10; in other words, to produce the combined mixture yield by growing pure stands would require 10% more land, i.e. the mixture gave a 10% yield increase. Identical calculations have been used in competition studies for many years but on a yield rather than a land-area basis. Terminology has varied, but most commonly L_a and L_b have been termed relative yields and LER the Relative Yield Total (RYT—de Wit and van den Bergh, 1965).

An important concept inherent in the use of LERs is that different crops, whatever their type or level of yield, are put on a relative and directly comparable basis. Replacement series diagrams could also be much more meaningful if plotted on this relative basis: this has been suggested in the literature (van den Bergh, 1968; Hall, 1974a) but has found little favour. As an example Fig. 1e and Fig. 1h show the data from Mixture 1 and Mixture 2 plotted in this way. Both sole crop yields are given the value of 1, so the diagrams in effect show LERs. This not only gives a better indication of the relative competitive abilities of the component crops, but also shows the actual values of any intercropping yield advantage: thus the 10% and nil advantage of the two mixtures is again clear.

3.2. Competition functions

In addition to the LER concept, there are also a number of 'competition functions' proposed in the literature to describe competitive relationships and which give some indication of yield advantages. These have been developed in plant competition studies but the ones listed below have all been tried in the analysis of intercropping experiments. Their possible use in this latter context is briefly discussed below.

The symbols used in these functions have varied a good deal: those used here are:

Y_{aa} = Pure stand yield of species a

Y_{bb} = Pure stand yield of species b

Y_{ab} = Mixture yield of species a (in combination with b)

Y_{ba} = Mixture yield of species b (in combination with a)

Z_{ab} = Sown proportion of species a (in mixture with b)

Z_{ba} = Sown proportion of species b (in mixture with a)

3.2.1. RELATIVE CROWDING COEFFICIENT. This was proposed by de Wit (1960) and examined in detail by Hall (1974a, 1974b). It assumes that mixture treatments form a replacement series. Each species has its own coefficient (k) which gives a measure of whether that species has produced more, or less, yield than expected. For species a in a 50:50 mixture with species b, it can be written:

$$k_{ab} = \frac{\text{Mixture yield of a}}{\text{Pure stand yield of a} - \text{Mixture yield of a}}$$

$$k_{ab} = \frac{Y_{ab}}{Y_{aa} - Y_{ab}}$$

For a mixture differing from 50:50 it can be generalised:

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

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. To determine if there is a yield advantage of mixing, the product of the coefficients is formed: this is usually designated K. If $K > 1$ there is a yield advantage, if $K = 1$ there is no difference and if $K < 1$ there is a yield disadvantage.

3.2.2. AGGRESSIVITY. This was proposed by McGilchrist (1965). It also assumes that mixtures form a replacement series and it gives a simple measure of how much the relative yield increase in species a is greater than that for species b. It is usually denoted by A. For any replacement series treatment it can be written:

$$A_{ab} = \frac{\text{Mixture yield of a}}{\text{Expected yield of a}} - \frac{\text{Mixture yield of b}}{\text{Expected yield of b}}$$

i.e.

$$A_{ab} = \frac{Y_{ab}}{Y_{aa} \times Z_{ab}} - \frac{Y_{ba}}{Y_{bb} \times Z_{ba}}$$

An aggressivity value of zero indicates that the component species are equally competitive. For any other situation, both species will 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 the difference in competitive abilities and the bigger the difference between actual and 'expected' yields.

3.2.3. COMPETITION INDEX. This analysis was suggested by Donald (1963). 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. If a given species has an equivalence factor of less than one it means it is more competitive (on a plant-for-plant basis) than the other species. The *competition index* is the product of the two equivalence factors. If the competition index is less than one there has been an advantage of mixing. The index has been tried in a number of intercropping situations (Willey and Osiru, 1972; Osiru and Willey, 1972; Lakhani, 1976), but has the disadvantage that the sole crops have to be present at a range of plant populations so that equivalent plant numbers can be estimated. This estimation is not a very accurate procedure, though Lakhani (1976) has suggested it can be improved by using some quantitative relationship between yield and plant population (Willey and Heath, 1969). But even with this refinement, accuracy of the final competition index is poor. Thus, although the concept is good, its practical use would seem to be limited and it is not considered further in this review.

3.2.4. COMPARISON OF RELATIVE CROWDING COEFFICIENT, AGGRESSIVITY AND LAND EQUIVALENT RATIO. Examples of some relative crowding coefficient, aggressivity and LER values are given in Table 1, calculated from an experiment which examined four genotypes of pearl millet in

TABLE 1

RELATIVE CROWDING COEFFICIENT, AGGRESSIVITY AND LAND EQUIVALENT RATIO VALUES FOR 50 : 50 INTERCROPS OF FOUR SORGHUM GENOTYPES WITH FOUR MILLET GENOTYPES
(International Crops Research Institute for the Semi-Arid Tropics, 1977)

Sorghum genotypes	GE 196			IS 9237			CSH 6			Y 75		
	k_{ms} k_{sm} K	A_{ms} A_{sm}	L_m L_s LER	k_{ms} k_{sm} K	A_{ms} A_{sm}	L_m L_s LER	k_{ms} k_{sm} K	A_{ms} A_{sm}	L_m L_s LER	k_{ms} k_{sm} K	A_{ms} A_{sm}	L_m L_s LER
MILLET GENOTYPES: GAM 75	*	1.62	1.06	1.56	.26	.61	1.13	0	.53	1.22	−.14	.55
	.33	−1.62	.25	.54	−.26	.35	1.13	0	.53	2.23	.14	.69
	*		1.31	.84		.96	1.27		1.06	2.72		1.24
GAM 73	4.56	.60	.82	1.27	.14	.56	1.04	.03	.51	1.22	−.02	.55
	0.28	−.60	.22	.72	−.14	.42	.92	−.03	.48	1.33	.02	.57
	1.28		1.04	.91		.98	.96		.99	1.62		1.12
PHB 14	5.67	−.10	.85	1.44	.14	.59	1.17	−.10	.54	1.08	−.28	.52
	0.25	.10	.20	.82	−.14	.45	1.78	.10	.64	4.00	.28	.80
	1.42		1.05	1.18		1.04	2.08		1.18	4.32		1.32
EX-BORNU	*	.89	1.03	2.45	.32	.71	2.57	.34	.72	2.45	.29	.71
	.16	−.89	.14	.64	−.32	.39	.61	−.34	.38	.72	−.29	.42
	*		1.17	1.57		1.10	1.57		1.10	1.76		1.13

k_{ms} and k_{sm} = 'Relative Crowding Coefficients' for millet and sorghum, respectively.
K = Product of 'Relative Crowding Coefficients'.
A_{ms} and A_{sm} = 'Aggressivity' values for millet and sorghum, respectively.
L_m and L_s = 'Land Equivalent Ratios' for millet and sorghum, respectively.
LER = Land Equivalent Ratio for combined millet and sorghum yields.
*Intercrop yield greater than sole crop yield resulting in negative value.

all combinations with four genotypes of sorghum as 50:50 intercrops (International Crops Research Institute for the Semi-Arid Tropics, 1977). It can be seen that for any given combination, all the functions clearly indicate which is the dominant and which the dominated genotype, and they all identify the equally competitive situation for CSH—6 sorghum + GAM 75 pearl millet. Also, both the crowding coefficient products and the LER values show which combinations do, or do not, give a yield advantage; the aggressivity values are not able to do this. However, a major drawback of the crowding coefficients is that they do not give a simple indication of the actual magnitude of any yield advantage. From this point of view, the LER values are preferable and also have the merit that they can be applied to any intercropping situation and not just replacement series treatments. It should be added, however, that a further possible use of the crowding coefficient may be that it provides a means of predicting the effects of competition in a situation other than those actually examined (i.e. other treatments in a replacement series). This is examined in Section 5.1.2 of Part 2.

3.3. Further consideration of land equivalent ratio

The usefulness of L_a, L_b and LER values can perhaps best be appreciated if all three of these parameters are presented graphically as in Fig. 2. L_a and L_b are plotted on the two axes and the LER value is then shown by the diagonal lines which join these axes. The sorghum/millet data referred to above are plotted in Fig. 2a. This clearly shows the actual level of intercropping advantage for any given combination and the proportions of each component which produced this. As an added refinement, the diagonal line rising from the origin (as shown) could be added: this is the 'expected' 50:50 yield, so points below it are where sorghum is dominant and points above are where millet is dominant. This type of diagram can also be used where the treatments are, say, different levels of some given factor, although conventional response curves may appear somewhat distorted. Fig. 2b shows the plant population responses for two row arrangements with maize/beans (Willey and Osiru, 1972). The diagram shows, for example, that the maize was dominant (compare with lines of 'expected' yield), that this dominance increased as plant population increased, and that the peak intercropping advantage for both treatments was at Population 3.

A criticism of the LER concept is that intercropping is effectively being compared with sole crop areas which are not predictable by the farmer and which cannot, therefore, form a realistic alternative. In theory this is true: the exact areas of sole crops involved in the comparison are determined by the final intercrop yields, whereas the farmer has to decide crop areas at sowing time. In practice, however, it seems likely that in the long term the farmer would adjust the sown area of each crop, whether intercropped or sole cropped, to achieve, on average, the proportion of each crop which he requires at harvest (e.g. for the reasons suggested under (iii) in Section 2). Moreover, the LER has the great merit that it gives an accurate assessment of the greater biological efficiency of the intercropping situation: for experimental purposes some calculation like this is essential. It must be emphasised, however, that when presenting intercropping results, the calculation of LER values does not eliminate the need for some presentation of absolute yields. The practical significance of LER values can only be fully assessed when related to actual yield levels.

It is appropriate at this point to comment on the very common practice of examining intercropping advantages by expressing yields in monetary terms. This does, of course, put different crops on a comparable basis. But unfortunately, the calculation of advantages is then almost invariably done by comparing equal *sown* proportions of intercrops and sole crops. As seen earlier, this is very likely to lead to bias because of differences

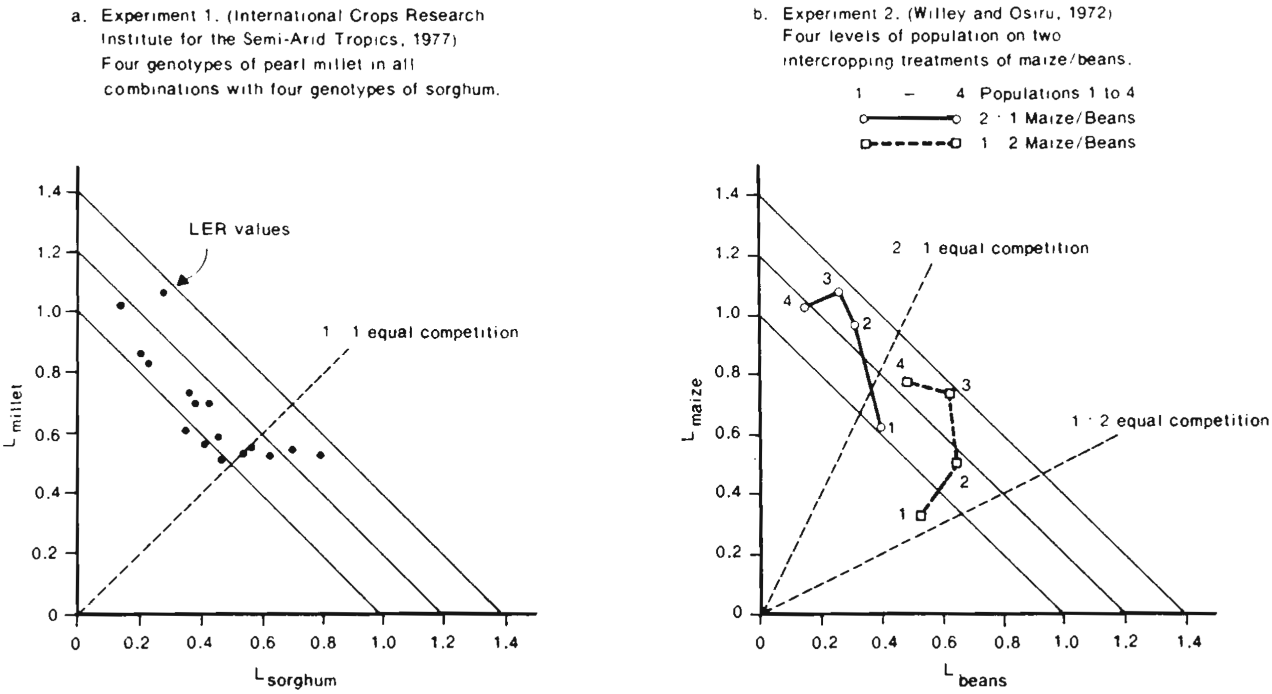

Figure 2. Land Equivalent Ratio diagrams for two intercropping experiments.

in yield proportions. This could again be avoided by calculating an LER based on monetary values (e.g. the relative land area required as sole crops to produce the *value* of yields achieved in intercropping), but this gives exactly the same figure as an LER based on yields. A more satisfactory use of monetary values would probably be to calculate the absolute value of the genuine yield advantage. For example, in Mixture 1 (Fig. 1f) it would be the value of the 10% yield increase indicated by the LER of 1.10. In practice this would be most easily calculated as follows:

$$\text{Monetary advantage} = \text{Value of combined intercrop yield} \times \frac{\text{LER} - 1}{\text{LER}}$$

This calculation does assume, however, that the appropriate economic assessment of intercropping should be in terms of increased value per unit area of land. Ryan (1978, Private communication) has pointed out that in subsistence situations the increased yield could well result in a farmer cultivating *less* land. He suggests that in these situations the economic assessment should be in terms of the value of land *saved*; this could probably be most easily assessed on the basis of the rentable value of this land. Whichever of these approaches is used, it is clear that some form of economic evaluation is usually desirable, in addition to whatever analyses are carried out on straight yields.

4. Biological Basis for Intercropping Advantages

4.1. Resource use

There can be situations where a given crop will actually grow better in the presence of another crop than as a sole crop (e.g. where there is a beneficial effect of shade—Willey, 1975). But usually a yield advantage occurs because component crops differ in their use of growth resources in such a way that when they are grown in combination they are able to 'complement' each other and so make better overall use of resources than when grown separately. In terms of competition, this means that in some way the component crops are not competing for exactly the same overall resources and thus inter-crop competition is less than intra-crop competition. Maximising intercropping advantages is therefore a matter of maximising the degree of 'complementarity' between the components and minimising inter-crop competition. On this basis, intercropping advantages are more likely to occur where the component crops are very different.

Probably the main way that complementarity can occur is when the growth patterns of the component crops differ in time so that the crops make their major demands on resources at different times. This type of complementarity is said to give better *temporal* use of resources. Its importance is indicated by some very substantial yield advantages that have occurred when there have been marked differences in the maturity periods of component crops, e.g. an 80% advantage with 85-day pearl millet/150-day sorghum (Andrews, 1972), up to 73% advantage with various 80- to 100-day crops/180-day pigeonpea (Krantz *et al.*, 1976), 20–60% with 85-day maize/120-day groundnut (International Rice Research Institute, 1974), 30–40% with 90-day maize/160-day rice (International Rice Research Institute, 1975), 55% with 85-day beans/120-day sorghum (Osiru and Willey, 1972), 38% with 85-day beans/120-day maize (Willey and Osiru, 1972). Advantages have also occurred where the only difference between component crops has been one of time rather than crop type, e.g. intercropping of early and late potatoes (Schepers and Sibma, 1976). Instances where three-crop combinations have given greater advantages than two-crop ones also emphasise the importance of this type of complementarity because the effects have largely been attributed to a better temporal distribution of crops (Hart, 1975; International Rice Research Institute, 1975; Krantz *et al.*, 1976; Wilson and Adeniran, 1976).

Baker (1974) considered temporal differences of such importance that he suggested that yield advantages were unlikely unless there was at least a 25% difference between two components or, if there were three components, unless the sum of the two shorter growing periods was less than 1.75 of the longest. In a latter paper, Baker and Yusuf (1976) tried to quantify this effect for some cereal mixtures by fitting a quadratic equation of yield advantage against difference in maturity. They estimated that no advantages would occur unless there was approximately a 30- to 40-day maturity difference.

Whilst emphasising the importance of temporal complementarity, it must be pointed out that yield advantage indicated by LERs may be misleading because they take no account of the differences in growing periods of the cropping situations effectively being compared (i.e. intercropping *v.* some of *each* sole crop), in practice, these differences may have a very important effect on the overall cropping systems. The basis of the problem is that the LER comparison assumes that no crop is grown after the harvest of the earlier maturing sole crop; and yet where maturity differences are large this could be so in practice. There is no easy answer to this problem, but it does illustrate that intercropping must always be compared with realistic practical alternatives. It also highlights the situation where temporal differences may be most beneficial, that is, where the effective growing season is longer than that of some required early maturing crop but not long enough for two sequential crops. In this situation the required early maturing crop grown as an intercrop component can ensure efficient early use of resources (especially if grown as a 'full' crop) and a later maturing component can ensure efficient use of any 'residual' resources.

In addition to temporal complementarity between component crops, *spatial* complementarity may also be possible. For example, it is often suggested that a combined leaf canopy may make better spatial use of light, or a combined root system may make better spatial use of nutrients and/or water. In general, there is less evidence for beneficial spatial effects, and certainly the mechanisms which may produce them are more a matter of conjecture than of fact. A difficulty is that, although it can be useful in theory to distinguish between temporal and spatial effects, in practice they are often inseparable. A similar difficulty exists in trying to distinguish the relative importance of the different growth factors: these are also very closely interrelated. However, since a better understanding of resource use is essential if intercropping improvement is to be put on a more scientific basis, a review of some of the possibilities is attempted in the following Sections.

4.1.1. LIGHT. Donald (1961) emphasized that light differed from the other resources in that it could not be regarded as a reservoir from which demands could be made as required: light is 'instantaneously available' and has to be 'instantaneously intercepted' if it is to be used for photosynthesis. Because of this, Willey and Roberts (1976) emphasized that light was probably the most important factor when better temporal use of resources was achieved. Baker and Yusuf (1976) also considered light of prime importance in their intercrops involving cereals of different maturities. Similarly, in maize/rice intercrops at the International Rice Research Institute (1975), although sole rice had a much higher leaf area duration than the intercrop, the latter was thought to derive its high yield advantage from the much better distribution of its leaf area over time. Lakhani (1976) also examined leaf area durations and found that increases of up to 27% were associated with yield advantages of up to 24%.

Considering spatial light use, Willey and Roberts (1976) stressed that given optimum plant populations, sole crops are themselves usually capable of achieving a peak value of light interception which leaves little scope for greater spatial interception by intercrops. Experiments in which readings have been taken at a few points in time (International Rice Research Institute, 1973; Fisher, 1975; Thompson, 1977), and from which it has been reported that intercrops intercept 'more light', may be difficult to interpret in the spatial sense because it is not usually possible to compare peak values of interception. In a recent experiment at ICRISAT (unpublished data) daily light readings were taken in a sorghum/pigeonpea intercrop throughout the season. Although the intercrops gave greater total dry matter yield and had a slightly greater leaf area index, their peak light interception of about 90% was virtually identical to the sole sorghum. Similarly, Lakhani (1976) achieved yield advantages of more than 20% in sunflower/fodder radish intercrops, but peak light interception values were no higher than those of the sole crops.

Thus if there is to be better spatial use of light, this has probably to be achieved through more efficient use of light rather than greater light interception. This can theoretically occur if light is better distributed over the leaves, either because of better leaf inclination or because of better leaf dispersion. Studies to date have suggested that these effects are likely to be of only minor importance. Leaf inclination has been studied extensively in grass mixtures in which attempts have been made to produce a more ideal canopy by combining a tall, erect leaved grass with a short, prostrate one. Only rarely have yield advantages been recorded (Alcock and Morgan, 1966; Rhodes, 1970) and even these have been associated with specific cutting regimes. Trenbath (1974) studied a comparable situation in mixtures of wheat cultivars using a simulation model. When he considered a theoretically ideal canopy containing non-overlapping leaves and no stems, and assuming an extreme difference in angle between an erect upper cultivar and a prostrate lower one, he found an increase in photosynthesis of only 8.7 % in competition with the cultivars being grown separately. When some overlapping, or stems, were introduced into the model this advantage rapidly decreased: he also stressed that less difference between the mean leaf angles of the two cultivars (which would be the case in practice) would further diminish the advantage. With respect to a better vertical distribution of leaves, Kasanaga and Monsi (1954) showed that on theoretical grounds high light intensities (e.g. in the tropics) would be better utilised by a canopy with greater vertical distribution. Pendleton and Seif (1962) examined this effect by mixing maize genotypes of different height, but no effect on yield was observed. Osiru (1974) on the other hand found that some yield advantages resulted from intercropping sorghum genotypes of different heights, but the maximum increase was only 9 %.

Evidence for useful improvement in spatial use of light may be lacking because component crops studied have been similar; where crop differences result in greater canopy differences, greater improvement may be possible. Major changes in leaf size, shape and angle are obviously possible and with respect to the canopy density factor mentioned above (Kasanaga and Monsi, 1954) it is possible to have a sparse canopy, say a tall cereal, for the high light intensities at the top of the canopy and a more dense canopy, say a compact legume, for the lower intensities at the bottom. There is also the possibility of combining crops which have different inherent responses to light. Thus the top of the canopy could consist of a component with a high light requirement and the bottom a component with a low light requirement; an obvious example here would be a tall C_4 crop combined with a short C_3 one (Crookston and Kent, 1976). It may also be possible to have components adapted to the qualitative changes in light which occur down the canopy (Allen *et al.*, 1975; Szeicz, 1975) though no specific evidence on which to base this seems available. A particularly good example of efficient spatial use of light would seem to be 'multi-storey' cropping, where crops ranging from tall trees to low growing annuals form different canopy layers (Nelliat *et al.*, 1974); each crop appears well adapted to its particular light niche and most of the factors discussed above are probably involved.

4.1.2. NUTRIENTS AND WATER. Any consideration of below-ground resource use inevitably involves a consideration of rooting patterns and studies on these have been few. One possibility is that component crops may exploit different soil layers; thus in combination they may exploit a greater total volume of soil. Trenbath (1974) considered this the cause of yield advantages in some mixtures of oat varieties and suggested that such differences in rooting patterns could occur because of the 'mutual avoidance' of different root systems (Raper and Barber, 1970; Baldwin *et al.*, 1972); this is simply the tendency for a crop to 'avoid' areas that have already been depleted of resources by an associated crop. But such avoidance can presumably also occur between roots of the same species, so it is doubtful if this can be regarded as a general advantage of intercropping; moreover, there is evidence that the roots of at least some crops intermingle freely (Lai and Lawton, 1962; ICRISAT, unpublished data). However, some tendency for avoidance may exaggerate natural differences between the rooting patterns of components. Thus there is evidence from a number of studies that a deeper rooting component may be forced even deeper by the presence of a shallow rooting component (Whittington and O'Brien, 1968; International Rice Research Institute, 1972; Fisher, 1976a, Lakhani, 1976).

Greater nutrient uptake by intercropping has been shown by several workers—e.g. for nitrogen (Dalal, 1974; Ibrahim and Kabesh, 1971; Kassam and Stockinger, 1973; Lakhani, 1976; Liboon and Harwood, 1975; de Wolff, 1970); for potassium (Dalal, 1974; Hall, 1974b); for calcium and magnesium (Dalal, 1974). This has very often been claimed as the basic cause of yield advantages, but usually it is impossible to determine whether greater uptake was the cause of or the effect of greater yields. Hall (1974b) showed that certain aspects of this could be resolved by calculating Relative Yield Totals (RYT ≡ LER), or crowding coefficients, for individual nutrients and comparing these with comparable values for total dry matter. Thus if, for example, an RYT for a nutrient is less than that for total dry matter, this probably indicates that it is being exploited less well than other resources by intercropping, and it may well be limiting the intercropping response. A higher value probably indicates that the nutrient is being better exploited by intercropping and is not limiting. This analysis does assume, however, that differences in competition for different nutrients will be reflected in differences in nutrient content in the crop. Hall (1974a, 1974b) successfully used this analysis to show that there was some complementary use of nitrogen in two grass/legume mixtures, an effect which he assumed was due to nitrogen fixation by the legume.

Apart from the possible differences in rooting pattern discussed above, the mechanisms by which nutrient uptake is increased are far from clear. One possibility is that, even where growing periods are similar, component crops may have their peak demands for nutrients at different stages of growth, a temporal effect which may help to ensure that demand does not exceed the rate at which nutrients can be supplied. A rather different temporal effect could occur where nutrients released from one crop, as a result of senescence of plant parts, are then made more readily available to another crop; for example, there is evidence that shade trees above certain crops can have the beneficial effect of bringing to the surface via leaf fall nutrients normally unavailable to crops (Willey, 1975). But more obvious causes arise, perhaps, from differences among component crops in their nutrient requirements, the forms of nutrients which they can readily take up, and their ability to extract them from the soil. Davies and Snaydon (1973) found that different strains of *Anthoxanthum* differed in their abilities to extract calcium and in their dry matter production per unit of calcium taken up. Also, Hall (1974b) showed that when soil levels of potassium were low, *Setaria* was much better able to extract this nutrient than an associated *Desmodium* crop. A further possibility is that interactions between the rhizosphere micro-organisms of component crops could benefit nutrient uptake (Kibani *et al.*, 1976; Shantaram and Rangaswami, 1967). The former workers observed interactions in maize/soyabean intercrops, but these could not be related to yield effects. The whole subject of nutrient uptake would seem to deserve much further study.

The effects of intercropping on water use have received even less attention than the effects on nutrient uptake and so far there is little evidence of beneficial effect. Baker and Norman (1975) suggested that better water use was probably a common cause of yield advantages in semi-arid tropical areas because this was basically the most limiting resource. Baker (1974) also tried to show theoretically that spreading peak water demands by temporal intercropping must give more efficient use of water. Kassam (1973) in Nigeria calculated that in the early stages of growth of a maize crop there was water surplus to requirements. He suggested that an early intercrop, such as millet, would help to utilise this and so improve water use efficiency. Two studies in which some aspects of water use have actually been measured may be of special interest. At ICRISAT in the sorghum/pigeonpea study (unpublished) referred to earlier, intercropping produced greater yields of dry matter during the period of sorghum growth, but total water use was unchanged; thus water appeared to be used more efficiently. Also, Lakhani (1976) measured the soil water status under intercrops of sunflower/fodder radish and found that, at given horizons, 'replacement' treatments of the two crops seemed better able to extract water than either sole crop.

4.1.3. NITROGEN IN LEGUME/NON-LEGUME COMBINATIONS. It seemed well established in the 1930s that, at least in pot studies, legumes could excrete nitrogen during growth and so benefit an associated non-legume (Nicol, 1935; Virtanen *et al.*, 1937; Wilson and Burton, 1938). However, the extent of this on a field scale and the factors which might affect it are much less clear. It has been suggested that excretion might be particularly likely where legumes are subjected to shading (Wilson and Wyss, 1937; Walker *et al.*, 1954), but this may only be important after good growth has already been made under high light conditions. Certainly, where legumes are continuously shaded their overall capacity for nitrogen fixation is likely to be impaired. A further factor is presumably the relative growing periods of the crops, for whilst it seems possible that an early legume may benefit a later maturing non-legume, such an effect seems less likely when the relative growing periods are reversed.

Considering the many intercropping studies which have included legume/non-legume combinations, it may seem surprising that so little information is available from field situations. But one of the problems is that experimental designs do not often allow a specific nitrogen benefit to be distinguished. Where any kind of replacement treatment is used (e.g. 50:50), any change in the non-legume crop from its 'expected' yield is the result not just of possible nitrogen transfer but also of other competitive and complementary effects. The only situation in which conclusions can really be drawn is where the presence of the legume produces a greater yield of non-legume than is achieved in sole cropping. In experiments in India, Singh (1977) demonstrated this effect when he added five different legumes to a crop of sorghum. Under rainfed conditions, averaged over two seasons and four spatial arrangements, the sorghum intercrop yield exceeded the sole crop yield with all legumes; increases ranged from 8.4 % with soyabean to 34 % with cowpea for fodder. A similar experiment under irrigated conditions, averaged over three spatial arrangements, gave smaller increases but cowpea again gave the highest increase (17.2 %). In both these experiments sorghum had an estimated two-thirds of its nitrogen requirement applied as fertilizer (60 and 80 kg/ha N for rainfed and irrigated crops, respectively). Similar experiments in India have been reported (Indian Agricultural Research Institute, 1976) in which the nitrogen contribution of intercrop legumes to maize was estimated to be 40 kg/ha from groundnuts and 25 kg/ha from mungbean. Other experiments suggesting similar though smaller advantages have been maize/groundnuts in northern Nigeria (Kassam, 1972), maize/soyabean in East Africa (Finlay, 1974), maize/beans in Colombia (Centro International de Agricultura Tropical, 1974) and maize/cowpea in Nigera (Wien and Nangju, 1976).

It must be appreciated, however, that even when some of the nitrogen fixed by a legume component is transferred to a non-legume component, this does not necessarily mean there is an advantage of intercropping. Strictly speaking, a genuine intercropping advantage occurs only if the fixation process, or the eventual use of fixed nitrogen by other crops, is more efficient than when the crops are grown separately but in some suitable sequence. With regard to the efficiency of the fixation process, observations at ICRISAT have suggested that pigeonpeas may nodulate better where the roots intermingle with those of intercropped sorghum. Thompson (1977) also reported an apparent increase in nodule number and weight on soyabean growing with maize, although results were not statistically significant. The obvious explanation for this is that the cereals depleted soil nitrogen, thus stimulating nitrogen fixation. If this is a real effect, it would seem to be a genuine advantage of intercropping. It is evident, however, that to examine the legume/non-legume situation fully it is necessary to examine not only current but also residual benefits. The latter aspect has been virtually ignored to date, though some work of Agboola and Fayemi (1972) has illustrated the importance of measuring both aspects. These workers showed that when maize was intercropped with mung there was a bigger current transfer of nitrogen than with cowpea; but an examination of the residual effects showed the opposite, with the cowpea having much the greater effect on the yield of a following maize crop.

4.2. *Yield stability*

It is frequently stated that a major reason for the predominance of intercropping in poorly developed agriculture is that it can give greater stability of yield over different seasons. The basis for this is that if one crop fails or grows poorly, the other component crop or crops can compensate; such compensation is not possible if the crops are grown separately. This is an additional and quite separate effect from that of 'spreading' risk by growing several crops; this latter is achieved whether the crops are intercropped or not.

Experimental evidence on yield stability is sparse. Fisher (1976b) reported a clear case of substantial compensation in a maize/bean trial at three sites. At one site the maize suffered from hail damage and disease but greater bean growth produced an LER of 1.87, whereas at the other two sites LER values were only 1.08 and 1.24. However, from the evidence of other experiments in different seasons, Fisher (1977) questioned whether greater stability occurred if moisture was the limiting factor. Harwood and Price (1975) have even questioned the whole concept of greater stability. In their experience crop failure often occurred after considerable inter-crop competition had already taken place and they concluded that sole cropping could often give greater stability. But a survey of the semi-arid areas of India by Jodha (1976), which showed that intercropping predominated in the lower rainfall/high risk areas, leaves little doubt about the farmer's attitude to the possibilities of improved stability. Similarly, Norman (1972) found that in northern Nigeria incomes were less variable where intercropping was practised.

Trenbath (1974) reviewed some evidence for stability in intra-species mixtures. His findings can be summarised as follows: in two studies there was no improvement in stability (Clay and Allard, 1969 in barley; Pfahler, 1965 in oats and rye); in four others there were marginal improvements (Byth and Webber, 1968, and Schutz and Brim, 1971 in soyabean; Frey and Maldonado, 1967 and Qualset and Granger, 1970 in oats); in a theoretical study, mixtures of genotypes were shown to offer little improvement unless the individual lines were themselves poorly adapted, and even then it was thought that the resultant stability would be unlikely to exceed that of the best individual lines. Two further studies have been reported where mixtures of hybrids appear to have given marginal improvements in stability (Ross, 1965 in sorghum; Funk and Anderson, 1964 in maize). But all these studies have involved very similar components; where bigger differences occur, it seems possible that the advantages may be greater. This is to some extent supported by a comprehensive study of barley/oat mixtures in the UK at six locations over 5 years (Daniel, 1955); although these crops do not differ greatly, mixtures gave a measurable improvement in stability.

In conclusion, there would seem to be a need for research to determine exactly how much stability intercropping actually provides in practice. Assuming that it is of significance, it would also seem desirable to ensure that any practices recommended to farmers do not provide less stability than traditional intercropping.

Part 2 will follow in *Field Crop Abstracts*, 1979, Vol. 32, No. 2.