INTERCROP AGRICULTURE

Vol. 32 No. 1 (1979) pp. 1-10

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Intercropping - Its Importance and Research Needs. Part II: Competition and Yield Advantages.
Intercropping—Its Importance and Research Needs.
Part 1. Competition and Yield Advantages

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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 relating to the intercropping situation and the lack of objective criteria for determining the 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 such relationships might 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 periods during which both crops are in growth, even though the term 'intercropping' should also imply that the crops are grown in separate rows, and that any arrangement where there is some mixing between the two crops should be defined as 'mixed cropping' (Andrews and Kariam, 1975; Freymann and Venkataraman, 1977; Kudchadkar, 1971). This linguistic distinction is difficult to adhere to in a review of this kind where general references are made both to research (very predominantly 'intercropping') and farming practice (very often 'mixed cropping'). Moreover, these two terms have often been used as synonyms. For simplicity, 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 'mixtures', 'component species', 'intercrop sole yield', 'sole yield', and 'combined component yield' respectively.

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 Ayer (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 wide-spread practice and is likely to continue for at least the foreseeable future (Armstrong, 1972; Dalmynag, 1971; Francis et al., 1975; Gutierrez et al., 1973; Norman, 1974; Okigbo and Greenland, 1975). It has also been realized that the 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 intercropping advantages.

A major cause of intercropping advantages lies in the fact that there is evidence 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 (Ayer, 1949: Baker and Norman, 1975: Barra, 1962: Crookston and Kent, 1976: First, 1974: International Rice Research Institute, 1972, 1975; Nickel, 1973; Pinchinat et al., 1975; Rahenga, 1977) and some of the possible mechanisms have been reviewed (Trenbath, 1975; Kanyuomo, 1973; Litsinger and Moody, 1975). But there have also been instances of poorer control (Sears, 1975; 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. For example, crop may provide physical support for another (Ayer, 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; Sideway and Bonnett, 1975).

It may 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 4.1. The latter, although such effects are likely to be rare, are almost certainly of less importance than any new disease (Risser, 1969). A more serious disadvantage is that it is 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, herb-
2. Criteria for Assessing Yield Advantages

It is not always appreciated that different intercropping situations may have to satisfy rather different requirements, and yield advantages are to be achieved. Yet it is important to recognize 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 recognized in India where the primary objective of many intercropping combinations 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, 1963; Donald, 1965), 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. 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. While this may be true for very similar crops, such as different grass species or different genotypes within a species, it may not be so where different types of crops are grown (see (iii) below).

(iii) Where the combined intercrop yield must exceed a combined pure stand 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 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 grown 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 Relationship

3.1. Competition and yield advantages

Most competition studies have examined two species growing in a 'replacement series', i.e. a series of mixtures 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 50:50; 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 which 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 recognized. The first (Fig. 1a) is when the can be termed mutual inhibition, it is rare in practice but has been observed by some workers (Ahlgren and Aamodt, 1939; Donald, 1946; Harper, 1966). 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 most the commonest situation (Figs. 1c and 1f), is where one species yields less than expected and the other more. This can be termed competitive 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 Moxley (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 when 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 axes; the diagonals are thus the pure stand yields of each species and the uppermost broken line becomes the 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 in all cases), a mixture of the two species is likely to exceed the pure yield of the higher yielding species. Conversely, if the dominant species is the lower yielding, the comparison is biased in favour of pure stands.
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 of 3.00 units of a and 7.00 units of b. From the appropriate pure stand proportions, vertical comparisons between the combined mixture yields and the pure stand 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 $L_e$, $L_s$, and $L_{ab}$, as such indicate the LER's for the intercrop yields of crops $a$ and $b$, respectively. As an example of the calculations of LERs, it was seen that the 50:50 mixture yields of Mixture 2 (Fig. 1) would have been produced from 0.77 ha of $L_e$, 0.33 ha of $L_s$, and 1.10 ha in other words, to produce the combined mixture yield by growing pure stands would require 10.5% 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 $L_e$ and $L_s$ 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. 1f show the data from Mixture 1 and Mixture 2 replanted on a relative basis. These diagrams do not plot the data. They indicate the relative advantage of the component crops, but also show the actual values of any intercropping yield advantage; 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 context is briefly discussed below.

#### 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 relative coefficient $k$ which describes: ---

For species $a$ in a 50:50 mixture with species $b$, it can be written:

$$M = \frac{Y_{ab}}{Y_{sa}} \cdot \frac{Y_{ab}}{Y_{sb}}$$

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

$$M = \frac{Y_{0a} \times Y_{0b}}{Y_{0a} \times Y_{0b}}$$

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:

$$A = \frac{M_{ab}}{M_{sa}} \cdot \frac{M_{ab}}{M_{sb}}$$

An aggressivity value of zero indicates that the competition 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 Oosu, 1972; Oosu and Willey, 1972; Lakhani, 1976), but has the disadvantage that the sole crops have to be present at a range of plant population so that equivalent plant numbers can be estimated. This estimation is not a very accurate procedure, though Lakhani (1976b) 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

For example the relative crowding coefficient, aggressivity and LER values are given in Table 1.
all combinations with four genotypes of sorghum as 

T GAM 75 1.56 1.36 1.56 1.56 1.56 1.56 1.56 1.56 1.56 

RELATIVE CROWDING COEFFICIENT, AGGRESSIVITY AND LAND EQUIVALENT RATIO VALUES FOR 

GE 196 IS 9237 CSH 6 Y 75 

Sorghum genotypes 

K, L, K' = "Relative Crowding Coefficients" 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.
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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. II) it would be the value of the 10× yield indicated by the LER of 1.10. In practice this would be most easily calculated as follows:

**Monetary advantage**

\[ \text{Value of combined intercrop yield} = \text{LER} \times \left( \frac{\text{LER} - 1}{\text{LER}} \right) \]

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 substance 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 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 land saved.

4. Biological Basis for Intercropping Advantages

4.1 Resource use

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 intercrop 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 intercrop competition. By 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 75% 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), 25% 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 Adeney, 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 been found to be additive. Baker (1974) and Adeney, 1976 tried to quantify this

![Graph](image-url)
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.

While emphasizing 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 vs. 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 bath component 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 requires careful planning and some realistic alternative solutions. It also highlights the situation where temporal complementarity 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 use of resources (especially if grown as a "tall" 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 complete canopy would have a high light-gathering capacity. However, this is not always the case as spatial use of nutrients and 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 components; 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 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 (1970), 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% by increasing spatial light use. Willey and Roberts (1976) concluded that, for growth of cereals, sole crops are themselves already capable of satisfying any additional light requirement 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 exhibit "more light", may be difficult to interpret in the sense because it is not usually possible to compare peak values of interception. In a recent experiment ICRIAS (unpublished data) daily light readings were taken in a sorghum-pigeonpea intercrop throughout the season. Although the intercrops gave greater dry matter yield and had a slightly greater leaf index, their peak light interception of about 90%, virtually identical to the sole sorghum. Similar results were obtained for sunflower-fodder radish intercrops, but light interception values were no higher than those of the sole crop.

Thus if there is to be better spatial use of light, there must be alterations to the intercrop system. A particularly good example of an ideally ideal canopy containing non-overlapping leaves was achieved by combining a tall leaved grass with a short, prostrate one. Only rarely have yield advantages been recorded (Alcek and Mant, 1966; Rhodes, 1970) and even then these have been associated with specific cutting regimes. Trehthun (1974) studied the comparable situation in mixtures of wheat using a simulation model. When he considered a theoretically ideal canopy containing non-overlapping leaves, he found an increase in photosynthesis of only 8.7% in comparison with the cultivars grown separately. When some overlapping, or the dense growth of some intercrop, was introduced into the model, this advantage was 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 advantage. With respect to a better vertical distribution of leaves, Kasanaga and Monsi (1954) showed that theoretical grounds high light intensities (e.g. in tropics) would be better utilized by a canopy with greater vertical distribution. Pendleton and Self (1962) examined this effect by mixing maize genotypes of different heights but not on yield advantages observed. Davis (1975) and the other hand found that some yield advantage resulted from intercropping sorghum genotypes of different heights, but the maximum increase was only 10%.

Evidence for useful improvement in spatial light use may exist when comparing intercrops with sole crops. A good example of this would be the work of Kasanaga and Monsi (1954) it is possible to have a sparse canopy, a tall cereal, for the high light intensities at the tips of the canopy and a more dense canopy, say a C4 legume, for the lower intensities at the bottom. This takes the possibility of combining crops which differ in their different inherent responses to light. Thus the top canopy could consist of a component with a high light requirement and the bottom a component with a lower light requirement; an obvious example here would tall C4 combined with a short C3 one (C3). In such cases it may be possible to have a more ideal canopy containing non-overlapping leaves, and even these have been associated with specific cutting regimes. Trehthun (1974) studied this effect by mixing maize genotypes of different heights but not on yield advantages observed. Davis (1975) and the other hand found that some yield advantage resulted from intercropping sorghum genotypes of different heights, but the maximum increase was only 10%.

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form different canopy layers (Nellist 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 possible reason that component crops may exploit different soil layers; thus in combination they may exploit a greater total volume of soil. Trendith (1974) considered that the cause of yield advantages in some mixtures of oat varieties and suggested that such differences in rooting patterns could be caused because of the mutual avoidance of different root systems (Raper and Barber, 1976; Boldewijn 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; ICRIAT, 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 (Whiteman and O'Brien, 1968; International Rice Research Institute, 1972; Fisher, 1976a; Lakhani, 1976).

Greater nutrient uptake by intercropping has been discussed above, the mechanisms by which nutrient uptake appears well adapted is Unlikely due to the higher value probably indicates that the nutrient is being more efficiently added to the roots. However, the tendency for avoidance may exaggerate natural differences. An example of this could be resolved by calculating Relative Yield Totals (RYT or LER), or crowding coefficients, for individual nutrients and comparing these with comparable values for total dry matter. Thus, 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 species, an effect which he assumed was due to nitrogen fixation by the legume. Apart from the possible differences in rooting patterns 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 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 are a result of senescence of plant parts.

Some studies have considered the possibility that certain crops can have the beneficial effect of bringing the surface leaf fall nutrients normally unavailable to crops. Willey (1975) showed this is unlikely, but more work has been done 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 rainfall 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 supplied 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 made; groundnuts in northern Nigeria (Kassa, 1972), maize/soyabean in East Africa (Finlay, 1974), maize/beans in Colombia (Centro Internacional de Agricultura Tropical, 1974) and maize cowpea in Nigeria (Wien and Nangui, 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 over a single cropping system can only occur if the residual effect of the nitrogen fixed by a legume proves superior (in terms of crop yield or soil nitrogen) to a similar amount of the nitrogen added as fertilizer. Thompson (1977) also reported an apparent increase in nodule number on cowpea 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 Fayeoro (1972) has illustrated the importance of measuring both aspects. These workers showed that when maize was intercropped with mung thistle 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 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 the greater bean growth produced an LER of 1.87, whereas at the other two sites LER values were only 1.00 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 experiment, crop failure often occurred after considerable intercrop 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 (1972), 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.

Trenchard (1974) reviewed some evidence for stability in the cereal pulse intercrop experiments of the late 1960's. As usual, in two studies there was the evidence for increased stability (Clay and Allard, 1969 in barley; Fisheo, 1971 in oats and ry; in four others there were marginal improvements (Byth and Webber, 1968, and Schutz and Brim, 1971 in soyabean; Fry and Maldonado, 1964 and Quatlet and Grainger, 1965 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 mixtures in the UK at six locations over 5 years (Damer, 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 the result of significance, it would also seem desirable to ensure that any practices recommended to farmers do not provide less stability than traditional intercropping.
Intercropping—Its Importance and Research Needs.
Part 2. Agronomy and Research Approaches*

R. W. Willey**

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Acknowledgments

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they are taken as 100, component populations can then be expressed on a simple relative basis, e.g. a simple intercrop treatment having half the sole crop optimum of each of two components is expressed as 50:50 component population. There is an important distinction between this approach and the 'replacement series' approach described earlier. In a replacement series, 'proportional populations' or 'proportions' are related to the sole crops of the series whatever their population and the two proportions must always add up to 100.

In this present suggested approach, component populations have more practical meaning because they are always related to sole crop optimum populations. Perhaps more importantly, all intercrop situations can be described, whether they fit a replacement series or not, e.g. an important practical situation such as full sole crop population of one crop plus half the sole crop population of another is simply described as 100:50.

As far as possible, component populations are used subsequently in this review, though 'proportions' are still used for reference to some of the experiments which used them.
rectangularity will have effects similar to those on sole crops but two further factors have to be distinguished. The first is the proportional areas allocated to each crop at sowing time. Often, the proportional areas are directly related to component populations: thus, if 50:50 component population is achieved by having equidistant alternate rows, proportional areas will also be 50:50. However, this direct relationship does not have to apply and component populations can be (and often are) varied independently. This will become clearer when examples are examined later. The second factor is how proportional areas are arranged with respect to each other. This is usually a matter of how ‘intimately’ the crops are mixed. Thus an intercrop which has proportional areas of 50:50 can be arranged as (i) alternate plants within the row, (ii) alternate rows, (ii) alternate ‘double’ rows, etc.

As will be seen below, the responses of intercrops to population and spatial arrangement are just as important, and in need of the same detailed study, as the responses of sole crops. A further consideration is that in many experiments the effects of these factors have often been ‘confounded’ with intercrop versus sole crop comparisons, making accurate assessment of intercropping advantages impossible. On this basis alone, they need to be better understood.

5.1.1. TOTAL POPULATION. One of the most important aspects which has emerged from recent experimentation is that where intercropping gives a yield advantage, the optimum population optimum may be higher than that of either sole crop. This can be seen from the three sets of data given in Fig. 3. Comparisons are facilitated by presentation of both yield and population on the relative bases emphasised earlier, i.e. optimum yield and optimum population for each sole crop are taken as 1 and 100, respectively. The cereal/legume data (Figs. 3a, 3b) were made only within the same population levels. The responses follow the typical ‘parabolic’ curves of reproductive crops (Holli day, 1960) and show particularly clearly that the optimum total populations for the intercropping treatments were appreciably higher than those of the sole crops. Fig. 3c shows a very different situation where sunflower/fodder radish intercrops were examined for total dry matter production in the UK (Lakhani, 1976) and where the experimental design was the same as for the two previous examples. These data show the instances where optimum populations have been much higher than have been associated with large yield advantages (e.g. in the Uganda data given above), but there are insufficient data available to test this critically. The situations where population increases are most likely to be needed, however, are those where there are large temporal differences in growth patterns of the components. For example, evidence from intercropping with 80- to 90-day cereals and 150- to 180-day pigeonpeas in India (Freyman and Venkateswarlu, 1977; International Crops Research Institute for the Semi-Arid Tropics, 1977; Shelke, 1977) suggests that both the cereal and the pigeonpea should be at their full sole crop optimum to ensure efficient use of early and late resources, respectively; the total population in intercropping is therefore twice that of either sole crop optimum (i.e. 100:100 component population). Because of these possible differences in population response, it has been pointed out that calculations of yield advantages should be made between intercrop and cereal/grain/legume replacement series at different total population levels. The responses follow the typical ‘parabolic’ curves of reproductive crops (Holliday, 1960) and show particularly clearly that the optimum total populations for the intercropping treatments were appreciably higher than those of the sole crops. Fig. 3c shows a very different situation where sunflower/fodder radish intercrops were examined for total dry matter production in the UK (Lakhani, 1976) and where the experimental design was the same as for the two previous examples. These data show the typical ‘asymptotic’ response of total yield (Holliday, 1960); thus for any given curve, optimum population is estimated as the minimum population showing maximum (or near maximum) yield. Although the data are less striking than with the cereal/legume intercrops, it is evident that the intercrop treatments were still responding at populations above the sole crop optimum.

Other workers have also shown the need for higher intercrop total populations (Baker and Yusuf, 1976; International Crops Research Institute for the Semi-Arid Tropics, 1977; International Rice Research Institute, 1974; Kassam, 1973; Shelke, 1977). Since the need for higher total populations presumably arises because of the ability of intercrops to make better use of resources, it seems likely that the extent to which the population must be increased should be related to the magnitude of the yield advantage. Certainly, some of the

![Figure 3. Response of intercropping to total population.](image-url)

buted by each component. This is such an obvious and important effect that it has been examined probably more than any other factor in intercropping. However, whilst the general effects of changing component populations might be self-evident, the specific effect in any given situation is far from predictable. This is because there is so little precise information on the competitive abilities of crops and the factors affecting them. It was seen in Section 3.2 that there are a number of ways of describing competitive abilities. In theory, one of these, de Wit’s relative crowding coefficient, can give a measure of competitive ability in one situation which can be used to predict effects in other situations. Unfortunately, this can only be used within a replacement series, so it can only predict the effect of changing proportions at a given total population. It is examined in this context with the data presented in Section 5.1. by predicting yields at one replacement series treatment (e.g. 2:1 proportions) from the actual data of the other treatment (1:2 proportions) and vice versa. The predictions are plotted in Fig. 4 as LERs for each population level. There are a component populations is to examine the population response of each crop independently. This is illustrated in Fig. 5, again for the three sets of data examined in the previous sections. Each response curve is obtained by plotting yield of a given component against its own population expressed over the whole intercropping area, i.e. the population of the other component is simply ignored. The maize/beans data (Fig. 5a) show that the maize response curves in intercropping were very similar to the sole crop response curve, whereas the responses of the beans were much modified. This is almost certainly because the maize was very much the dominant crop. This is supported by the sorghum/beans data (Fig. 5b); Osiru and Willey (1972) had reported that in this experiment the sorghum was dominant in the 2:1 treatments (sorghum: beans) but the beans were dominant in the 1:2 treatments. This is clearly reflected in the response curves, which were similar to that of the sole crop when a given component was dominant but not when it was dominated. A similar situation is shown for sunflower/fodder radish (Fig. 5c). Sunflower/fodder radish. Sunflower/fodder radish.

Figure 4. Prediction of LER values in three intercropping experiments using de Wit’s crowding coefficient.

number of missing points because the coefficients cannot cater for situations where a given component has a higher intercrop yield than its sole crop: this happened quite often in the data where the sole crop population was above optimum. The results do not in fact look very promising, predicted LER values seldom bearing much relation to actual values. In particular, the more comprehensive data for sunflower/fodder radish showed that predicted values for the 2:1 treatment consistently underestimated the LERs and the competitive ability of fodder radish. However, the data in Fig. 5 illustrate some of the crop sets of data were from replacement series at both levels of population and the yield response of each component to increase in its own population was 'confounded' with equal increase in population of the other component. Furthermore, there was also some 'confounding' of spatial arrangement between curves, e.g. when a species was the major component it occupied two rows out of three and when it was the minor component it occupied only every third row. Thus the modified response curves of the minor components could have been partly due to poorer spatial arrangement.
Some suggestions for avoiding these effects are made later. On the basis of evidence available to date, however, it seems reasonable to suggest that the more dominant a component, and the more favourable its spatial arrangement, the more likely it is to show a population response in intercropping similar to that in sole cropping, where a component is dominated and has less favourable spatial arrangement its response curve may differ greatly from that in sole cropping. The latter type of component would seem to be the one in most need of investigation.

5.1.3. SPATIAL ARRANGEMENT. It was pointed out earlier that even when the space allocated to component crops is directly related to component populations, the 'intimacy' of the arrangement can still vary. It has often been suggested that to get maximum benefit from any complementary effects, crops should be as intimately associated as possible and there have been experiments which support this (Andrews, 1972; International Rice Research Institute, 1973). But there have also been reports of no effects (Evans, 1960; Herrera et al., 1975) and others where increasing intimacy has decreased yield. For example, Osiru (1974) found that in alternate row arrangements of sorghum genotypes of different heights, the shorter genotypes grew very poorly and overall yield decreased. In less intimate arrangements the shorter genotype yielded better and yield advantages occurred. Very similar effects have been reported by Krantz et al. (1976) where the allocation of space to the component crops is altered without changing component populations. A particularly good example is the cereal intercropping research carried out in many parts of India. Since the objective here is to produce a full cereal crop with some additional yield of a second crop, a common approach has been to manipulate the spatial arrangement of the cereal to create more space for the second crop but without reducing cereal yield. The most effective arrangement has been 'pairing' of the cereal rows, e.g. changing a sole crop row width of 45 cm to pairs of rows 30 cm apart with 60 cm between pairs; this allows a second crop to be grown in the 60 cm between pairs.

A considerable body of work has shown that cereal yield can be maintained over a surprising range of spatial arrangement patterns and that appreciable increase in yields of the second crop can often be achieved (All-India Coordinated Research Project for Dryland Agriculture, 1972; Freyman and Venkateswarla, 1977; Shehke, 1977; Singh and Rathore, 1978; Singh et al., 1972; Singh, 1977; Tomer and Saini, 1978). Similar effects have been shown where a cereal has been 'hilled' to create more space for a component legume (Francis et al., 1975; Centro Internacional de Agricultura Tropical, 1974; International Crops Research Institute for the Semi-Arid Tropics, unpublished data) although one report has indicated a decrease in yield from this technique (Dalal, 1974). Further experiments in which space allocation was changed at constant component populations were reported by Krantz et al. (1976); a number of combinations at 50:50 component populations gave yield advantages in alternate rows and these could be appreciably increased at other row arrangements particularly susceptible to shading, some degree of 'grouping' of the crops may give greater advantages by ensuring that the lower component receives a reasonable amount of light.

There is another important aspect of 'grouping' where the allocation of space to the component crops is altered without changing component populations. A particularly good example is the cereal intercropping research carried out in many parts of India. Since the

Figure 5. Population response of individual component crops in three intercropping experiments.
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(1976) showed this predominance in his survey of the semi-arid tropics of India and even indicated that as more farming inputs became available, farmers tended to move out of intercropping, especially where irrigation was one of the inputs. A similar situation prevails in northern Nigeria where Oguntowara and Norman (1973) found that intercropping was more frequent in areas where the level of technology was lower. But farming practice may well reflect a desire for yield stability rather than possible, no advantages in any given season. Some experiments have supported traditional beliefs by showing lower LEVs at higher levels of nitrogen inputs (International Rice Research Institute, 1975—maize/soybean). However, a recent experiment on sowing timing was reported by Kassam. (1972) found that intercropping was more frequent in areas where the level of technology was lower.

In later experiments (1973) found that intercropping was not frequently used in northern Nigeria where Qgun owora and others sowing of nitrogen input (International Rice Research Institute, 1975—maize/soybean). However, a recent experiment on sowing timing was reported by Kassam. (1972) found that intercropping was more frequent in areas where the level of technology was lower.

An important feature of this experiment was that, because of an increase in the level of yields, the Monetary Advantage (part Section 3.3) was 79% higher with 120 kg N ha than at the nil nitrogen treatment. Similar effects have been reported by Oelsglele et al., 1975, and Fisher (1975) has even reported some maize beans experiments which showed advantages in a wet season but not in a dry season.

Perhaps the main evidence that advantages occur at high fertility levels is that most experiments have been carried out under comparatively favourable circumstances, i.e. at research stations. However, some researchers have even stressed the high levels of fertilizer inputs they used (Mynett and Quivey, 1972; Baker, 1974; Lokhande, 1974). In particular, the objective of examining intercropping at high input levels and against a background of good moisture supply (Baker and Quivey, 1972; Quivey and Wille, 1972; Oyar, 1974). It would seem logical, however, for the effect of changes found that intercropping depend on the base causes of advantages for any given intercropping combination. Where advantages depend on temporal differences between the crops, there is no reason to believe that they will disappear at higher fertility levels. As suggested earlier, light is one of the main factors used more efficiently in such combinations and thus better available of water and nutrients will perhaps only ensure that the light is fully exploited. Conversely, if advantages are due to better nutrient or moisture use, then such advantages are likely to diminish or even disappear if the supply of these factors is adequate.

A further question to be asked, and again one on which there is little information, is whether the fertilizer response of individual crops is different in intercropping from that in sole cropping. This is particularly important when the fertilizer requirements of the component crops differ widely. A good example is the use of nitrogen fertilizer in legume-non-legume combinations. Some experiments have shown that the response of a cereal may be the same in cereal/legume intercropping as in sole cropping, but the cereal has either been grown at the same population as the full sole crop as in the case of sorghum pigeonpea experiments at ICRISAT (unpublished data) or has been a very dominant crop as in the case of sorghum groundnut experiments reported by Kassam (1972). This situation may change where a crop in the dominant one or where it does not constitute a major component. In ICRISAT (1972—maize/soybean).

A final point is that because component crops may influence each other's competitive abilities. Again, the best example is the legume non-legume situation. It has apparently been shown that whereas at lower nitrogen levels the legume may be reasonably competitive, at higher nitrogen levels the legume is much less competitive. Consequently, legume/non-legume combinations may produce a much smaller proportion of the final yield (International Rice Research Institute, 1972—maize/soybean, Kassam, 1972—sorghum/groundnuts; Thompson, 1977—maize/soybean). There appear to be two closely related factors involved.

5.3. Relative sowing times

In some areas where intercropping is practised, the sowing times of the component crops differ widely. In parts of Africa which experience a dry season, a very sparse population of a drought resistant crop such as pearl millet is often sown with the first showers of the rainy season; as the rains set in, other crops are interplanted with the first one. In this instance the sowing is staggered, probably because it allows the cropping system to be adjusted to early season moisture supply and, of course, it spreads the sowing time labour peak. But whilst the sowing of the later component crop is staggered, its effects on yield advantages merit some consideration. For example, in ICRISAT (1975—maize/soybean), there may be a potential for greater yield advantages. This is supported by some studies which have shown increased advantages from having a later sowing of the later component (Francis et al. 1974—International Rice Research Institute, 1975—maize/soybean).

5.4. Genotype Identification

The need for identification of suitable genotypes in intercropping has been stressed by many workers and it seems likely that this offers just as much scope for yield improvement as it does in sole cropping. From his competition studies, Hepper (1965) concluded that the most satisfactory way of comparing pure line and intercropping genotypes is to grow genotypes which are eventually to be used in a given intercropping system in single crop experiments at some stage to be evaluated in that situation. For some crops, this may be relatively straightforward as for a traditional intercropping system at ICRISAT, pigeonpeas are selected by adding a cereal between the rows of the pigeonpea genotypes.
requires no more land than sole crop selection and, because the pigeonpea usually has a negligible effect on the very dominant cereal, yields of the cereal can be ignored. Often, however, incorporating a second crop will require much greater experimental resources and, of course, the problem is increased enormously if a given crop commonly occurs in a number of very different combinations. Despite these difficulties, however, a much more serious attempt at selection needs to be made in the future.

The objectives of selection can be very simply stated as the selection of genotypes which minimise inter-crop competition and maximise complementary effects. In practice, this assumes a greater knowledge of competitive and complementary processes than is currently available, but some general points can be made. It was seen earlier that one of the major causes of complementarity was temporal differences in growth patterns and these effects are easily recognised. Thus, anything which can be done to increase these temporal differences may well be worthwhile. Achieving earlier maturity of the early component is likely to be a valid and acceptable effect. On the other hand, delaying the maturity of the later one requires a longer growing period and, as emphasised in the previous section, the acceptability of this may depend on the overall cropping system and the length of the available growing period.

At present, selection is probably limited to improving the leaf canopy. Here the attitude to selection probably has to vary with the extent to which a crop is dominant or dominated. In the former case the aim should be to select characters which, without being associated with an undesirable yield loss, reduce competition against the second crop; the advantage is then reflected in increased yield of the second crop. Thus, there are a number of reports in which reducing the height of a dominant cereal has resulted in higher yields of associated crops (Andrews, 1974; Thompson, 1977; Vorontsov et al., 1976). (Francis et al., 1975, reported decreased bean yields with a shorter genotype of maize, but the maize was grown at a higher population and other factors may therefore have been involved.) Even with a dominated crop there may still be some scope for reducing its competitive effect on the other component. Ween and Nangju (1976) reported that an erect, determinate cowpea had less competitive effect on maize than did some indeterminate ones. But the main aim with the dominated crop is to select genotypes which grow well in what is essentially an environment modified by the dominant crop; with specific reference to light, this usually means low in intensity and also especially poor in photosynthetically active wavelengths. In this situation, genotype response is much more difficult to predict. Apart from the more obvious aspects of leaf angle, shape, size, etc. (the general features of which are already determined by the choice of crop), almost nothing is known about such characters as inherent response of different genotypes to low light levels. Thus, much greater efforts may be required to select suitable genotypes for crops which form the dominated component.

Ideally, one objective of selection programmes should be to identify specific plant characters which can form the basis for further selection. But much selection is likely to continue to be done on a trial and error basis. Hamblin et al. (1976) proposed a scheme for identifying promising intercropping lines in a breeding programme. This involved growing lines of one crop in combination with lines of a second crop and plotting yields of a given crop (regression lines for maize) for each genotype. Ideally, one line was distinguished from another by a test statistic, the predicted mean difference (PMD). This involved growing lines of one crop in combination with lines of a second crop and plotting yields of a given crop (regression lines for maize) for each genotype. Ideally, one line was distinguished from another by a test statistic, the predicted mean difference (PMD).

...

The yields of genotypes of one crop are plotted against the mean yield of each genotype of the second crop. The advantage of using mean yields of second crop genotypes is that these give a better measure of the average competitive abilities of the genotypes (in terms of the Finlay and Wilkinson analysis these means can be regarded as measures of different intercropping "environments"). Fig. 6a illustrates in terms of LER values a typical pattern that might be obtained, in this instance millet yields against mean sorghum yields; Fig. 6b and e give the fitted regression lines for both crops. It must be emphasised, however, that these regression lines are given purely for illustrative purposes, since the range of pearl millet environments was much too limited to allow extrapolation of sorghum genotype performance. Also, a background statistical analysis would normally be required to indentify whether the response could be validly described by linear relationships. The differences between responses were statistically significant.

Taking an analogy from other analyses, the slope of a given regression line can be taken to indicate general intercropping compatibility and the deviations from a "specific intercropping compatibility". The advantage of plotting in LER terms is that the values indicated by the regression lines are particularly meaningful. Ignoring, for convenience, the negative sign of the slope, a slope equal to 1 indicates a genotype which can be expected to give the same relative yield of one crop, a slope less than 1 a genotype more likely to give an advantage in 'environments' where the other crop is dominant, and a slope greater than 1 a genotype more likely to give an advantage when it is itself dominant. The expected advantage from a given genotype also depends on the "height" of the regression line; this could be indicated by the mean yield, but experimentally this depends on the range of "environments" being examined. It would be more useful, therefore, to define a "value" for a standard population on the horizontal axis. Thus a 50\% compatibility value could be defined as the "expected" L value of a given genotype when an associated crop gives an L value of 0.5. To take two examples, the sorghum genotype B has a 50\% compatibility value of 0.08 and a slope virtually equal to 1 (again ignoring sign); thus this genotype can be expected to give a yield advantage of about 18\% (LER equals 1.18) whatever pearl millet genotype it is in combination with. Similarly, pearl millet genotype d with a 50\% compatibility value of 0.74 and a slope of 0.7451, could be expected to give a 24\% yield advantage when an associated sorghum crop gives a 50\% yield, and this advantage would be expected to decrease if the millet genotype was dominant but increase where the associated sorghum crop was dominant.

Accepting the obvious desirability of selecting in the intercropping situation, there may still be some selection possible in sole cropping. To this end, various workers have tried to relate sole crop performance with intercropping performance (Finlay, 1974; International Rice Research Institute, 1974; Baker, 1974; Francis et al., 1975). Not surprisingly, relationships seem to have been promising where the component crop is the dominant one but not when it is the dominated. Specific characters may still be identifiable. For example, for pigeonpea as a second crop, an SC equal to two rows (this character is a desirable one because it requires less land for a given harvest of early intercrop) the pigeonpea should ideally spread rapidly across the rows. This would be facilitated by greater plant flexibility being stressed by Andrews and Hassan (1975) and Baker and Grout (1976). This can be examined relatively easily by growing two genotypes with different populations of a suitable yield population response function involving the pigeonpea (Willey and Heath, 1969). This flexibility can be quantified in a single parameter. However, it should be emphasised that there may be only certain types of intercropping situations where this flexibility is desirable. Where there are large temporal differences between species and it is desirable at some stage of growth for each component to use the space not being efficiently used by the other component, this character is obviously desirable; similarly, it is desirable where greater stability of yield is required. However, where species are growing over the same period of time this character may well result in an undesirable degree of intercrop competition.

6. Experimental Designs and Statistical Analysis

The area of plant population and spatial arrangement is the one where the need for improved designs is most pressing, especially to separate effects due to the density of species. As noted earlier (Section 5.1.), Willey and Ostra (1972) introduced the use of replacement arrangements at different populations to separate genuine intercropping effects from those due to changes in population pressure. It was pointed out in Section 5.1.2. however, that this approach does not give a completely independent assessment of the population response to each component. A possible approach which partly solves this problem is to keep the population (and usually the spatial arrangement) of one crop fixed whilst varying the population of the other (International Rice Research Institute, 1974). In this way both the relative "advantage" of the second crop (a) is changed systematically. As shown, the size of change in a is quite large but in practice this would be limited to no more than about 10\% between adjacent rows. Although this particular design
only gives changes in crop a, the full factorial arrangement can be achieved by running other sub-blocks at different standard populations of crop b. This is an arrangement currently being tried at ICRISAT (1977). Advantages over the rain designs are that the parallel row arrangement is much more typical of actual practice and row lengths can be adjusted to give whatever harvest area is required. It is theoretically possible to vary the populations of both crops systematically, e.g. by systematically varying the spacing of crop b along the row in Fig. 7a. But this reduces the harvest area for a given treatment to a single plant or to a small group of plants. To achieve any degree of field accuracy, replicates would have to be numerous and thus it is doubtful if such designs would be worthwhile in practice.

A rather specific type of systematic design is illustrated in Fig. 7d. This examines the arrangement of two rows of one crop between fixed single rows of a second crop. It has been used in some Indian studies with various crops (Sheke, 1977) to determine the optimum spacing of 'paired' rows of one crop between single rows of a second crop (see Section 5.1.3).

The particular point to note is that they are grown at optimum population and spacing. Without jeopardising the aims of the experiment, controls should be kept to a minimum so that the maximum possible proportion of the experiment is allocated to intercrop treatments. As an example, in the simplest possible design of two sole crops and one intercrop gives only one-third of the plots as intercrop treatments. The 'efficiency' of this design could be improved by incorporating more intercropping treatments of the same two crops. This simple effect is less obvious as designs get more complex. Considering genotype experiments which examine single treatments of all combinations of the same number of genotypes of each crop, 2 x 2, 3 x 3, 4 x 4 and 5 x 5 designs give, respectively, 50%, 60%, 67%, and 71% of the plots as intercrop treatments (assuming one genotype is included as a sole crop). So these designs get more efficient as they get larger. It is also worth noting that comparable genotype experiments which hold the genotype of one crop constant must always have less than 50% of the plots as intercrops.

As a general comment on design, the best method to use in both experiments must include proper 'controls' (i.e. sole crop treatments). As a general rule, controls should be included for all crops being examined in order that a valid assessment of yield advantages can be made. In many intercropping experiments carried out to date this has not been done. An exception may be where intercropping aims to achieve a full yield of a 'main' crop with some additional yield of a second crop. In this situation a control for the second crop could be eliminated on the basis that intercropping is an alternative only to a sole 'main' crop. Controls should, of course, give maximum yield for the level of management being considered.
twice. In many instances the latter would give more repetition of plots than desirable, but the general idea is useful one. Where all combinations of genotypes of different crops are being examined, the use of a 'strip-plot' design may be a possibility (Mead, 1978, personal communication). In this design, strips of genotypes of one crop are laid out across strips of genotypes of the other crop; the inclusion of a 'nil-genotype' strip for each crop provides the sole plots, though this does give rise to a blank plot where these strips cross. Apart from being a convenient layout, this has the advantage over a split plot design that it does not favour the mean genotype effects of one crop more than the other.

6.3. Statistical analysis

It is not within the scope of this review, nor the expertise of the author, to make detailed comments under this heading, but some simple observations may be helpful.

A straightforward procedure, and one that is usually necessary to some degree, is to analyse the crops separately. This can be done using a 'reduced' design which simply involves ignoring the sole treatments of the crop not being considered. This is particularly useful for examining parameters which are only applicable to one of the crops. When component populations are directly related to non-orthogonal term structure, the advantage that it gives a direct indication of competitive effects.

No intercropping situation can be fully analyzed without combining the crops in some way, however, and this is where difficulties arise. A straight addition of yields is usually meaningless where they are of very different types. In some instances yields can be reduced to some common biological denominator such as yield of protein, dry matter, digestible nutrients, etc. A more realistic alternative is to assign a monetary value to each crop. But it must be appreciated that a normal analysis of variance then gives a comparison of variance between actual treatments. This can be useful, but where the assessment of an intercropping advantage depends on a comparison with a combined sole crop yield, the analysis of this comparison is not included. Simple statistical tests have been made between actual and 'expected' yields for one crop component (Hill, 1973; Innis and Jones, 1977) and these could possibly be extended to make comparisons with 'expected' combined sole crop yields. A particularly useful procedure would be a straightforward analysis of variance of LER values because the 'expected' combined sole crop yield is always equal to one. However, the nature of the distribution of LER values seems to be uncertain and thus the statistical validity of this procedure is at present doubtful. McGilchrist and Trenbath (1971) suggested a possible way of doing this with a diallel design (i.e. all binary combinations of a crop). This appears complex. Hopefully, this particular problem will receive the attention of biometricians in the future.

7. Summary and Conclusions

This review stresses the importance of intercropping in agriculture to which the possible advantages of different intercropping situations can be assessed, suggesting that the most important practical situation is where intercropping has to provide a higher yield than where both component crops are grown separately. Different ways of putting this assessment on a quantitative basis are considered and it is concluded that the Land Equivalent Ratio (LER) is probably the most useful term presently available. Later, it is emphasized that this term should be used in conjunction with some indication if absolute yields and, where appropriate, some economic evaluation.

Better use of growth resources as a result of complementary effects between component crops is proposed as one of the major sources of yield advantage; the mechanisms by which this may occur are discussed. It is concluded that temporal complementarity is likely to produce bigger advantages than spatial complementarity, but that this whole field needs much further study.

Nitrogen fixation and yield stability aspects are also considered; in both, only limited evidence is available and this is often contradictory. Here again, more research is suggested. The various aspects of plant population and spacing in intercropping are defined and it is recommended that, where possible, the 'confounding' of these in experimental design should be avoided. Evidence of the need for higher total populations than with sole crops is presented, it is suggested that these higher populations may be specially justified where there are large temporal differences between component crops. Little evidence is available on the possible effects on the availability of nutrients and water on yield advantages and this is clearly an area needing further study. It is concluded that a selection of compatible genotypes should also receive more emphasis and the objectives of such research are discussed. Finally, some recent comparisons are made on experimental designs and statistical analyses.

I wish to acknowledge former colleagues at Makerere University, Kampala, Uganda and Reading University, UK, where some of the research quoted was carried out. I also thank present colleagues at ICARAT for many helpful comments and the Director for permission to publish.

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