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Intercropping—Its Importance and Research Needs. Part 2. Agronomy and Research Approaches*

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CONTENTS

5. Agronomic Relationships

5.1. Plant population and spatial arrangement

For sole crops, the different aspects of plant population and spatial arrangement are well understood. Plant population defines the number of plants per unit area, which determines the *size* of the area available to the individual plant. Spatial arrangement defines the pattern of distribution of plants over the ground, which determines the *shape* of the area available to the individual plant. For crops regularly arranged in rows, spatial arrangement can be concisely defined by the rectangularity, which is the ratio of the inter-row spacing to the intra-row spacing (Holliday, 1963).

For the intercropping situation, plant population and spatial arrangement aspects are more complex. With regard to plant number, both *total population* (all components) and *component population* (each component) have to be distinguished. The main problem here is that, in terms of the plant population 'pressure' on resources, a single plant of one crop is seldom directly comparable to a single plant of another crop (Willey and Osiru, 1972). This can be overcome by regarding optimum populations of sole crops as comparable. If 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 important, 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 referring to some of the experiments which have replacement series treatments at different total population levels.)

With regard to spatial arrangement of intercrops,

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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.

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 optima.

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

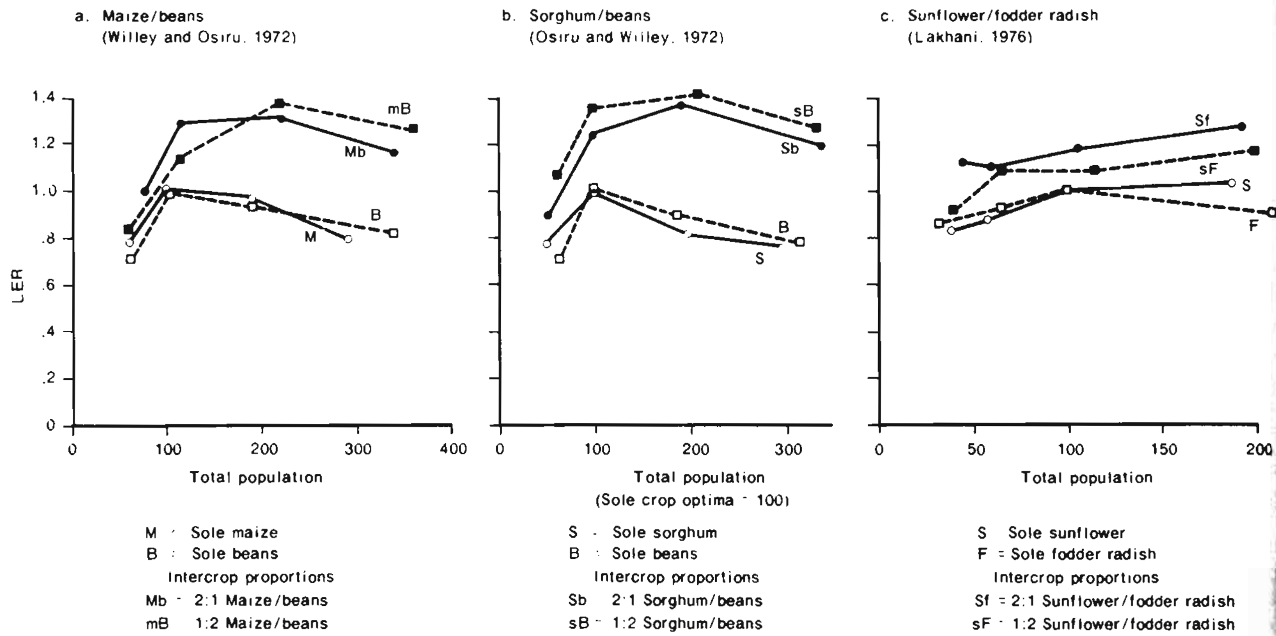


Figure 3. Response of intercropping to total population.

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 when intercropping gives a yield advantage, the total 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 taken from studies in Uganda (Willey and Osiru, 1972; Osiru and Willey, 1972) and were produced from '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

instances where optimum populations have been much higher 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 pigeonpea 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 sole crop at their respective optimum populations (Huxley and Maingu, 1978); certainly if comparisons are made only within the same population levels, a very misleading indication of the practical value of intercropping may be given. The procedure need not invalidate the definition of LER given earlier (Section 3) since a population change is often easily and cheaply achieved and need not be regarded as a change in 'level of management'.

5.1.2. COMPONENT POPULATIONS. Component populations mainly determine how much of the final yield is con 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 5.1.1. 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 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; for the other treatment they overestimated both these effects. These results emphasise that competitive ability is not a constant and quantifiable function for a given crop. It is in fact dependent on the population situation itself. Willey and Osiru (1972) and Lakhani (1976) had earlier pointed out from these data that all the component crops became relatively more competitive if they formed a larger proportion of the total population; they also stressed that as total population increased, the dominant crop became even more dominant.

Bearing in mind the big yield responses to increase in total population, an obvious approach to examining 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 was very dominant in the 2:1 treatments and it responded in very much the same way as the sole crop. It was not quite so dominant in the 1:2 treatments and its response was modified. Fodder radish was always very dominated and its reponse curves showed no real relation to those of the sole crop. Somewhat similar effects have been obtained in other experiments (Centro International de Agricultura Tropical, 1974; Francis *et al.*, 1975; Shelke, 1977).

However, the data in Fig. 5 illustrate some of the problems of experimental designs in intercropping. All three sets of data were from replacement series at four 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.

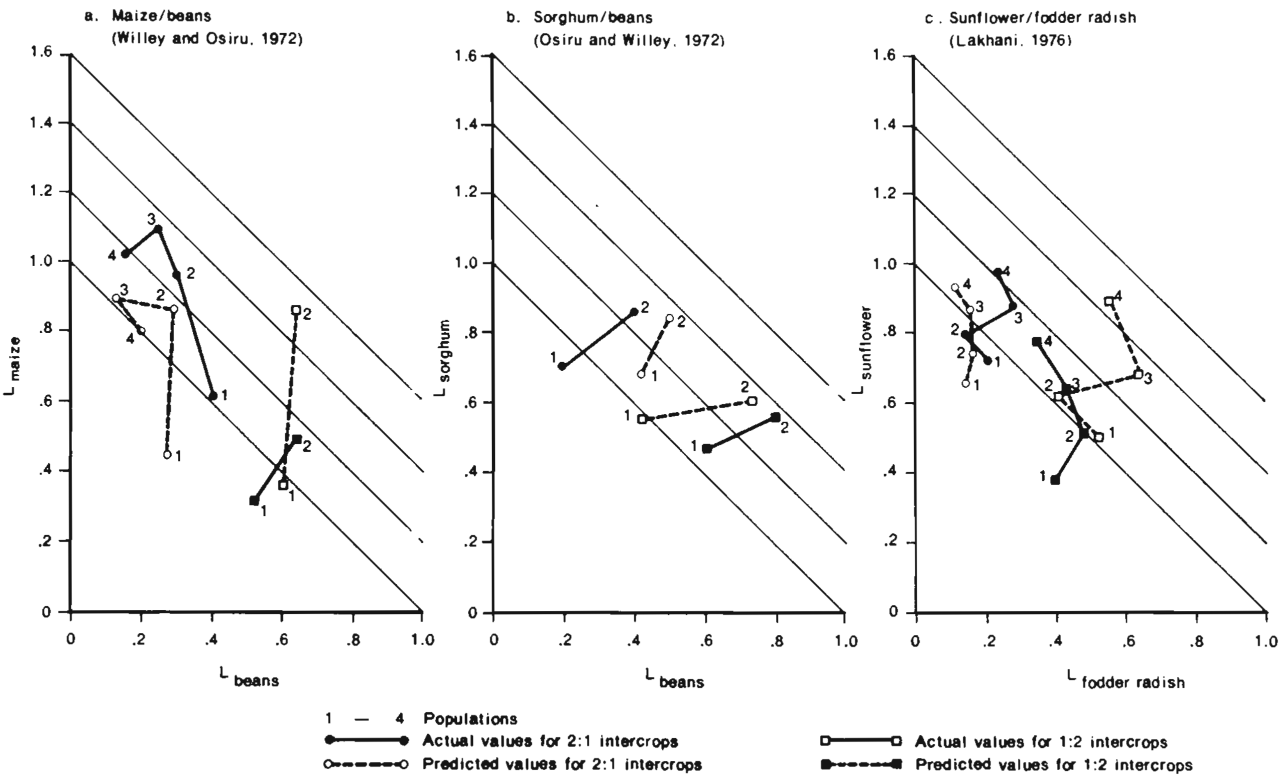


Figure 4. Prediction of LER values in three intercropping experiments using de Wit's crowding coefficient.

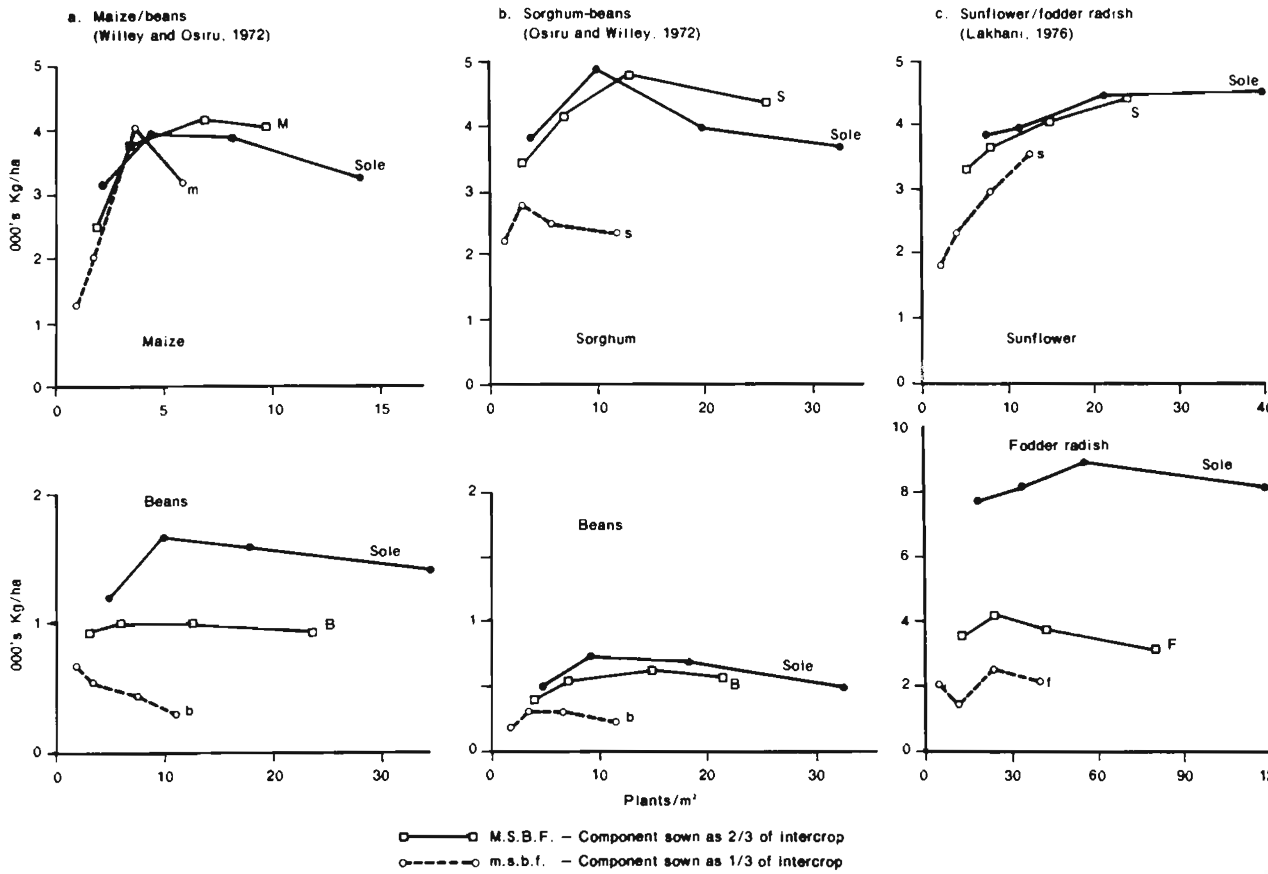


Figure 5. Population response of individual component crops in three intercropping experiments.

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 Pendleton and Seif (1962) with maize genotypes. Thus, it may well be that where the shorter component is 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 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 Venkateswarlu, 1977; Shelke, 1977; Singh and Rathore, 1978; Singh *et al.*, 1973; 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 International 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.

5.2. Reponse to nutrients and water

Perhaps the most important question that needs to be asked under this heading is whether intercropping advantages are affected by changes in the level of productivity. There is undoubtedly a long-standing belief that advantages may occur only in low-fertility situations and this probably arises from the fact that intercropping predominates in poorly developed agriculture. Jo...

(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 Ogunfowora 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 yield advantages in any given season. Some experiments have supported traditional beliefs by showing lower LERs at higher levels of nitrogen input (International Rice Research Institute, 1975—maize/soyabean). However, a recent experiment on sorghum/pigeonpea at ICRISAT (unpublished data) examined nitrogen levels of 0, 40, 80 and 120 kg/ha and achieved LERs of 1.46, 1.52, 1.38 and 1.46, respectively. An important feature of this experiment was that, because of an increase in the level of yields, the Monetary Advantage (see Section 3.3.) was 79 % higher with application of 120 kg N/ha than at the nil nitrogen treatment. Similar effects have been reported by Oelsligle *et al.*, 1975, and Fisher (1977) has even reported some maize/beans experiments which showed advantages in a wet season but not in a dry season.

Probably 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. Several researchers have even stressed the high levels of fertilizer input they used (Kassam, 1972; Baker, 1974; Lakhani, 1976). In particular, the series of experiments in Uganda, which showed consistently large advantages, had the specific objective of examining intercropping at high input levels and against a background of good moisture supply (Willey and Osiru, 1972; Osiru and Willey, 1972; Osiru, 1974). It would seem logical, however, for the effect of changes in fertility level to depend on the basic causes of advantages for any given intercropping combination. Where advantages depend on temporal differences between components, 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 availability 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 especially 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 is the dominated one or where it does not constitute a major component.

A final point is that because component crops may differ in their abilities to respond to given nutrients, the level of nutrient availability may have considerable influence on their relative competitive abilities. Again, the best example is the legume/non-legume situation. It has frequently been shown that whereas at lower nitrogen levels the legume may be reasonably competitive, at higher levels it is very often dominated and thus produces a much smaller proportion of the final yield (International Rice Research Institute, 1972—maize/soyabean; Kassam, 1972—sorghum/groundnuts; Thompson, 1977—maize/soyabean).

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 interspersed 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 whatever the practical reasons for staggered sowing, its effects on yield advantages merit some consideration and these have been examined in a number of studies.

There appear to be two closely related factors involved. The first is the effect on temporal differences between the crops. Where these differences are reduced, the evidence suggests that yield advantages diminish, presumably because of the reduced temporal complementarity between the crops. For example, Osiru and Willey (1976) found that whereas an advantage of 20 % occurred in an experiment in which an 85-day bean and a 120-day maize were sown together, this completely disappeared if sowing of the bean was delayed by 28 days. On the other hand, where temporal differences are increased, 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.* 1975; International Rice Research Institute, 1973). An important practical point here is that when temporal differences are increased by staggered sowing, this increases the total growing period. In some situations, e.g. where continuous cropping is possible, this may raise questions of the efficiency of production over time. In other situations, particularly where the potential growing period is longer than that of either component crop but not long enough for two sequential crops, staggered sowing may be a very valuable way of ensuring that some crop is present on the land for the full period of possible growth.

The second factor which determines time-of-sowing effects, and one which may considerably modify the effects just discussed, is that an earlier sown crop becomes more competitive and a later sown one less competitive than when they are sown simultaneously. Thus, two very comprehensive studies in which temporal differences were increased by progressively delaying the sowing of one component (Institute for Agricultural Research, 1977—cotton sown late in cereals; Vorasoot *et al.*, 1978—sorghum sown late in legumes) found that the yield advantages were diminished because of very poor yields of the later component. However, Francis *et al.* (1975) found that sowing bush beans two weeks before maize gave the best balance of competition and the highest yield advantages, showing that in some circumstances this change in relative competitive ability could be beneficial.

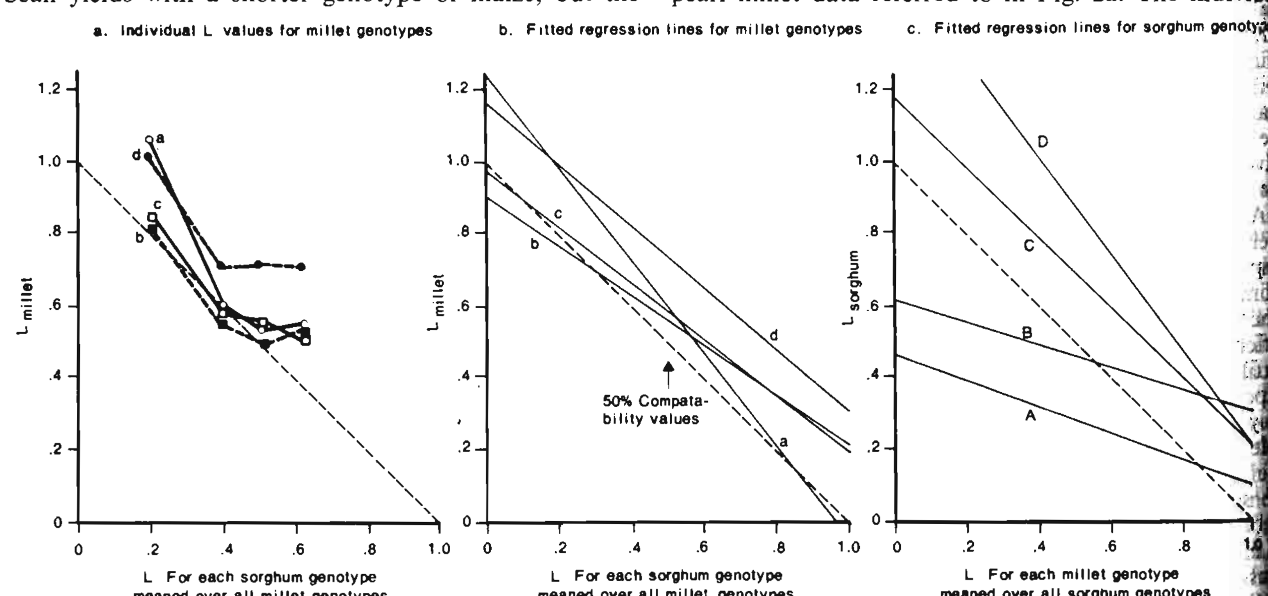
5.4. *Genotype identification*

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, Harper (1963) emphasised that 'the behaviour of mixed stands is not predictable from the behaviour of pure stands' and there seems little doubt that genotypes which are eventually to be used in a given intercropping situation must at some stage be evaluated in that situation. For some crops, this may be relatively straightforward. For example, in the breeding programme at ICRISAT, pigeonpeas are selected by adding a cereal between the rows of the pigeonpea genotypes; this 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.

With regard to selecting for improved spatial complementarity, so little is known about root systems that, 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; Vorasoot *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. Wien 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 line against the yield of each line with which it was combined. (In fact, this is analogous to the LER graph illustrated in Fig. 2, except that yields are not expressed in relative terms.) These workers pointed out that the most promising lines would be indicated by the points furthest from the origin (i.e., those with the highest LER) and the patterns of response of genotype combinations would give some indication of 'combining abilities'. This approach could be usefully developed to predict the likely intercropping performance of established genotypes by incorporating some elements of the Finlay and Wilkinson (1963) analysis of genotype-environment interaction. This is illustrated in Fig. 6 for the sorghum/pearl millet data referred to in Fig. 2a. The individual



		General intercropping compatability (regression slope)	50% Compatability Value (y at x = 0.5)
Millet genotypes	a	−1.2646	0.60
	b	−0.7183	0.56
	c	−0.7962	0.57
	d	−0.7451	0.74
Sorghum genotypes	A	−0.3943	0.27
	B	−0.3086	0.46
	C	−0.9829	0.68
	D	−1.4171	0.87

Figure 6. Illustration of an analysis of intercropping compatibility in a pearl millet/sorghum genotype experiment (International Crops Research Institute for the semi-Arid Tropics, 1977).

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 yield pattern that might be obtained, in this instance millet yields against mean sorghum yields; Fig. 6b and c give the fitted regression lines for both crops. It must be emphasised, however, that these regression lines are given here 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 identify whether the response could be validly described by linear relationships and whether differences between responses were statistically significant.

Taking an analogy from other analyses, the slope of a given regression line in Fig. 6 can be taken to indicate '*general intercropping compatibility*' and the deviations from it '*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 intercropping advantage (or disadvantage) with all genotypes of the other 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 magnitude of any 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 an 'expected' value for a standard point 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 0.68 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 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 intercrop performance (Finlay, 1974; International Rice Research Institute, 1974; Baker, 1974; Francis *et al.* 1975). Not surprisingly, relationships seem to have been promising where a crop is the dominant one but not when it is the dominated. But specific characters may still be identifiable. For example, the pigeonpea programme at ICRISAT has identified 'spreading' genotypes by examining response to wide rows: this character is a desirable one because after harvest of an early intercrop the pigeonpeas should ideally spread rapidly across the rows. The need for greater plant flexibility has been stressed by Andrews and Kassam (1975) and Baker and Yusuf (1976). This can be examined relatively easily by growing a genotype at two widely different populations and if a suitable yield/population response function involving some linear relationship is used (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 result in an undesirable degree of intercrop competition.

6. Experimental Designs and Statistical Analysis

6.1. Plant population and spatial arrangement designs

The area of plant population and spatial arrangement is where the need for improved designs is most pressing, especially to separate the various aspects discussed earlier (Section 5.1.). Willey and Osiru (1972) introduced the use of replacement series treatments 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, 1972, 1973; Francis *et al.*, 1975; Shelke, 1977; Freyman and Venkateswarlu, 1977). A more comprehensive design is currently being tried at ICRISAT. At a given row arrangement (or possibly a series of row arrangements) the population of each crop is varied independently simply by changing within-row spacings. A factorial with a range of populations of each crop allows both optimum total population and optimum component populations to be determined.

It is evident, however, that if traditional methods are used to examine these population and spatial arrangement effects, the experiments required are very large. A number of workers have tried to overcome this problem by using systematic arrangements based on designs suggested for sole crops (Bleasdale, 1967; Nelder, 1962). The main advantage of these designs is that the need for guard rows between treatments is eliminated and so large ranges of treatments can be examined on a relatively small area. They can be very useful to gain preliminary information on basic relationships. Great care should be taken in trying to interpet them in absolute terms (e.g. in determining actual yield responses) and they should most often serve only as useful forerunners of conventional experiments.

Fig. 7 illustrates four systematic designs which have been used in intercropping experiments. The first (Fig. 7a) was used by Willey and Lakhani (1976) to examine changes in proportions (brought about by changing row number) in sunflower/fodder radish intercrops. It can be useful where little is known about competitive abilities and how these are affected by row arrangements. Fig. 7b illustrates a more usual type of systematic design, namely a 'fan' design. This has been used by Huxley and Maingu (1978) for a number of crop combinations. The particular design illustrated shows total population changes at constant proportions, but many other arrangements are possible. Unfortunately, fan designs have the limitations that harvest areas tend to be particularly small; also, given positions within the fan do not always give results typical of comparable situations in more conventional designs.

Some of the disadvantages of the fan designs can be overcome by the type of design illustrated in Fig. 7c. In the part of the design shown, the within-row population of one crop (b) is kept constant and the population of the second crop (a) is changed systematically. As shown, the rate 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

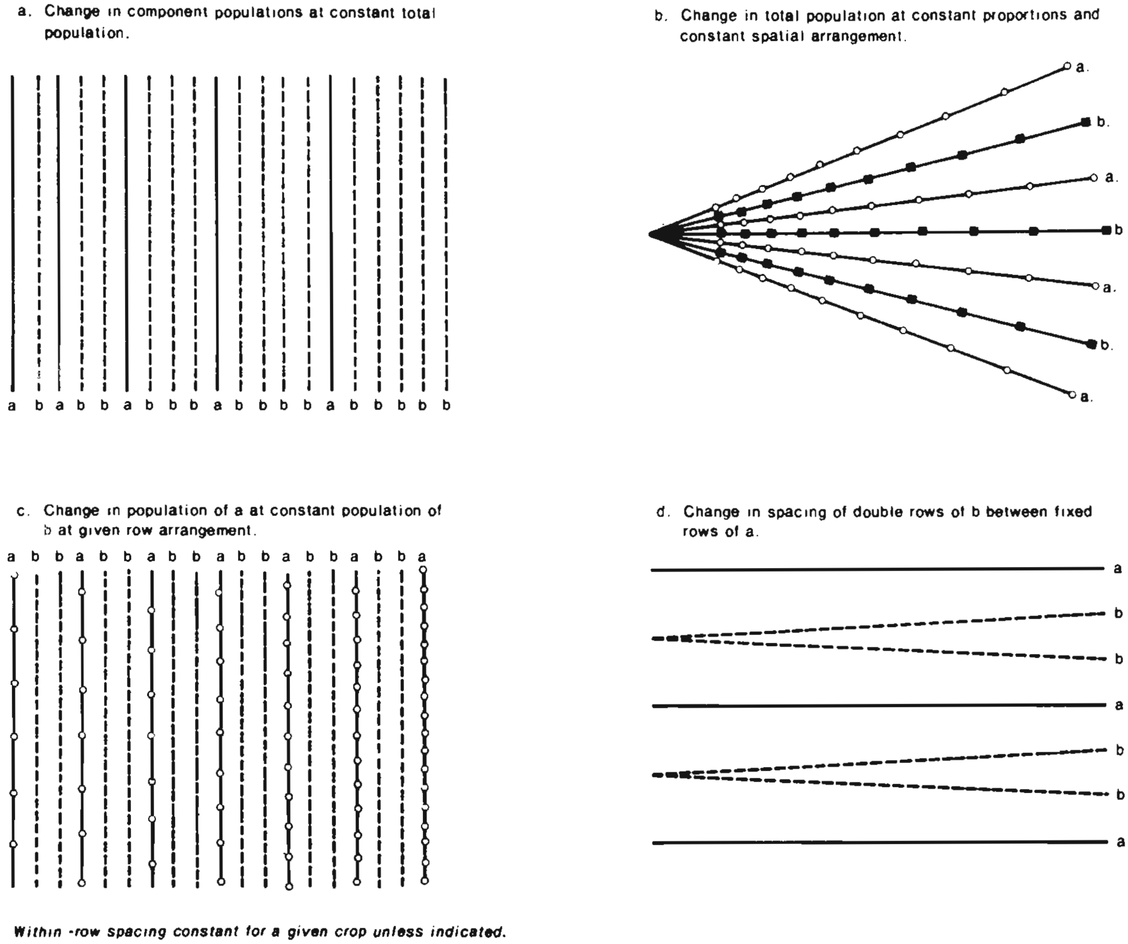


Figure 7. Examples of systematic designs used in intercropping experiments.

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 fan 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. 7c. 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, replications 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 (Shelke, 1977) to determine the optimum spacing of 'paired' rows of one crop between single rows of a second crop (see Section 5.1.3.).

6.2. General comments on experimental designs

One simple but very important point is that 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. The particular point to note is that they are grown optimum population and spacing.

Without jeopardising the aims of the experim controls should be kept to a minimum s that maximum possible proportion of the ex riment allocated to intercrop treatments. As an example, simplest possible design of two sole crops and one inte crop gives only one-third of the plots as interc treatments. The 'efficiency' of this design could improved by incorporating more intercropping tre ments of the same two crops. This simple effect is obvious as designs get more complex. Considering ge type experiments which examine single treatments of combinations of the same number of genotypes of crop, 2 × 2, 3 × 3, 4 × 4 and 5 × 5 designs gi respectively, 50%, 60%, 67 and 71% of the plots intercrop treatments (assuming every genotype is cluded as a sole crop). So these designs get more effic as they get larger. It is also worth noting that compar genotype experiments which hold the genotype of crop constant must always have less than 50% of plots as intercrops.

As a general comment on designs, the best guid that they should reflect the need to exam objec efficiently rather than the need to conform to con tional designs which may be easier to lay out and anal One of the main problems is that although the in cropping treatments themselves often form a bala factorial arrangement, the control treatments are us 'additional'. This means that split plot designs are possible and greater reliance may have to be put simple randomised blocks. Innis and Jones (1977) balanced lattice designs to examine mixtures of co cultivars in Uganda, but had to repeat some treatm to be able to do this. When examining all binary mix of five cultivars, they repeated one sole crop twic give a 4 × 4 lattice; but when examining seven cult they repeated one sole crop thrice and the other sole twice. In many instances the latter would give more repetition of plots than desirable, but the general idea is a 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 proportional sown areas, it is also entirely valid to analyse yield per plant (or yield per row); this has the advantage that it gives a direct indication of competitive effects.

No intercropping situation can be fully analysed 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 only 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 any one crop component (Hill, 1973; Innis and Jones, 1977) and this could presumably be extended to make comparisons with 'expected' combined sole crop yields. A particularly useful procedure would be a straight 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 range of genotypes of one species) but 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 and the need for much more research in this field. It defines criteria by 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. However, it is emphasised that this term should be used in conjunction with some indication of absolute yields and, wherever 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 designs 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 especially necessary where there are large temporal differences between component crops. Little evidence is available on the possible effects of the availability of nutrients and water on yield advantages and this is clearly an area needing further study. It is concluded that identification of compatible genotypes should also receive more emphasis and the objectives of such research are discussed. Finally, some brief comments are made on experimental designs and statistical analysis.

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