Intercropping studies with annual crops

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Abstract. This paper tries to illustrate how beneficial interactions between crops can be exploited to increase the overall output of a cropping system. Growth studies with sorghum/pigeonpea and millet/groundnut are described to show how intercropping systems can achieve much larger yields than sole crops by using environmental resources more fully over time or more efficiently in space. Data from moisture stress studies are presented to illustrate that these advantages of intercropping can be even greater under stress conditions.

Possible nitrogen benefits from legumes in intercropping systems are discussed with particular reference to a study on maize/groundnut. Weed, pest and disease control are considered and some effects of a sorghum intercrop on the incidence of pod borer and wilt disease in pigeonpea are described. Evidence for improved yield stability in intercropping systems is provided from a review of 94 experiments on sorghum/pigeonpea.

It is emphasized that intercropping is especially beneficial to the small farmer in the low-input/high-risk environment of the developing areas of the world but some brief comments are made on its applicability in more developed conditions.

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Most farmers have to grow a number of different crops for a variety of reasons: for example, to spread environmental or marketing risks, to distribute inputs such as labour reasonably uniformly throughout the season, or, at the subsistence level, to provide a range of different foods and other products for their own consumption. This means that farmers are concerned not only with the production of individual crops but also with the integration of crops into an overall system. It follows, therefore, that research aimed at raising a farmer's output must not limit its approach to improving individual crops but must also seek to improve cropping systems.

At its simplest, a cropping system can be defined as a combination of crops in both time and space, and the basic biological requirement of a productive system is that it should provide a continuum of efficient crop growth for as much of the potential growing period as possible. This is a simple enough concept but actual practice can be complex where several crops are grown and interactions occur between them. This complexity is particularly great in the intercropping system where two or more crops are grown together on the same piece of land in competition with each other. At the same time, however, the intercropping system is perhaps the best example of how interactions between crops can be exploited to produce considerable yield benefits. The system also illustrates the important point that benefits due to a system *per se* do not depend on costly inputs such as new seed, fertilizers or sprays, which are so often associated with raising the yields of individual crops; the benefits of intercropping are achieved simply by growing crops together rather than separately.

This paper mainly describes some of the results from intercropping studies of annual food crops at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). It presents quantitative evidence of the more important crop interactions that have been found and it discusses some of the possible mechanisms of these interactions. Moreover, because intercropping has long been regarded as a rather primitive practice, appropriate only to very traditional farming systems, we briefly consider the wider role that intercropping may play in more developed conditions.

Better use of environmental resources

The beneficial interaction that is perhaps most widely applicable in intercropping systems is the better use of environmental resources. This is illustrated with reference to two intercropping combinations, sorghum/pigeonpea and millet/groundnut, both of which have been studied in considerable detail at ICRISAT.

Sorghum/pigeonpea is one of the commonest combinations of crops in India and it is typical of many combinations throughout the world where a rapid-growing, early-maturing crop is grown with a slower-growing, later-maturing one. The sorghum grows for three-four months, maturing about the end of the rainy season; the pigeonpea usually flowers just after the sorghum harvest and it grows for a further two-four months, surviving mainly on the residual soil moisture. The farmer's main objective with this combination is to grow a reasonably 'full' yield of the staple cereal (i.e. as near as possible to a sole sorghum yield). The pigeonpea is introduced to provide some 'bonus' pulse yield, but only to the extent that it does not seriously jeopardize sorghum yield; Traditionally, the farmer has achieved these objectives by sowing predominantly sorghum, with only the occasional rows, or plants, of

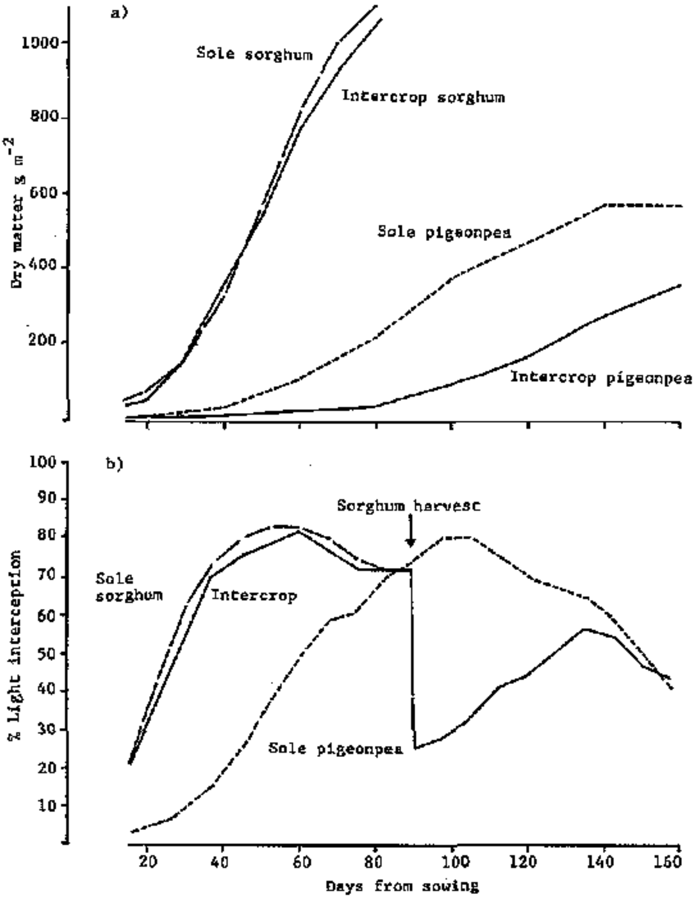

FIG. 1. Dry matter accumulation and light interception in sorghum and pigeonpea sown as sole crops and as a two-row sorghum : one-row pigeonpea intercrop (means of 1977, 1978 and 1979).

pigeonpea; however, while this method maintains sorghum yield it produces very little pigeonpea.

Fig. la shows the growth patterns of an improved sorghum/pigeonpea system where the row arrangement was two sorghum rows : one pigeonpea row and each crop was sown at its full population as a sole crop. The sorghum was an early, high-yielding hybrid, the pigeonpea was an improved type, and both crops were well fertilized. The results are the means of three years, 1977, 1978, and 1979.

Sorghum growth and yield was very good and intercrop yield was only a little less (5%) than the sole crop. Thus, despite the much higher proportion of pigeonpea than in traditional systems, the farmer's primary objective of maintaining virtually a full cereal yield was fulfilled; this has been ascribed to the high sorghum population that was maintained in the intercropping system (Natarajan & Willey 1981a). Slow initial growth of the pigeonpea crop was even further reduced by the sorghum intercrop. At the time of sorghum harvest, the dry matter yield of the intercrop pigeonpea averaged only 16% of the sole pigeonpea. From then on, however, the effect of the high population of the pigeonpea became apparent and the crop was able to make a relatively rapid recovery to produce a dry matter yield equivalent to 53% of the sole crop, a much higher proportion than in traditional systems. A further feature of this intercrop pigeonpea was that, because the competition from the sorghum reduced only its vegetative growth, it achieved a harvest index (30%) appreciably higher than the sole crop (22%). This improved efficiency of dry matter partitioning helped the pigeonpea to produce a substantial seed yield, equivalent to 72% of the sole crop. Looking at the system in total, therefore, we can see that for a sacrifice of only 5% in sorghum yield a 72% yield of pigeonpea was added.

Millet/groundnut is a combination used on lighter soils and it is found in both India and West Africa. Unlike the sorghum/pigeonpea combination, it is typical of crop combinations where there is little difference between the growing periods of the two crops but some difference in canopy height; more specifically, of course, it is typical of the cereal/low canopy legume combinations that are so prevalent in many parts of the world. The yield objectives of farmers seem to vary a good deal but the important groundnut cash crop is usually the major component, with the millet reduced to a minor role.

Fig. 2a shows the growth patterns and yields of a one row millet : three rows groundnut intercropping system where the within-row spacing of each crop was the same as its respective sole crop and plant populations were therefore equivalent to row proportions (25%:75%). For most of the growing period, accumulation of dry matter in the intercrop groundnut was less than the 75% sole crop 'expected' yield, indicating that its growth was being depressed by the millet. But it was able to recover from this effect towards the end of the season, especially after the millet harvest, and at final harvest actual yield was similar to 'expected' yield. In contrast, dry matter accumulation in intercrop millet was more than twice its 25% sole crop 'expected' level and at final harvest yield was 62% of the sole crop. Combining these dry matter yields into a relative yield total gave an overall advantage for intercropping of 36%; for seed yields the advantage was a little less (25%) because of small decreases in the harvest indices of both millet and groundnut..

The manner in which resources were utilized more efficiently in these two intercrop combinations is indicated by the light interception pattern and the

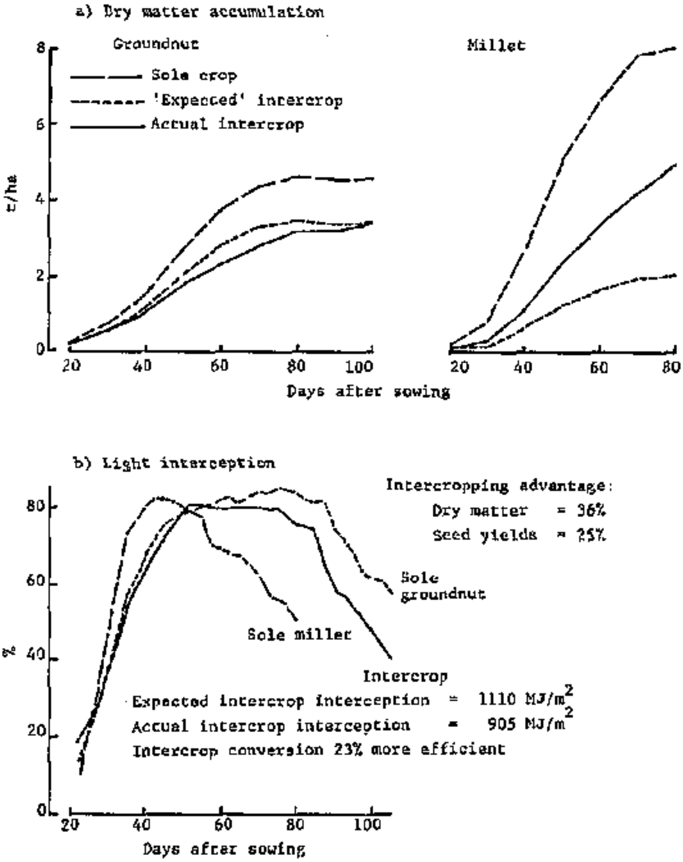

FIG. 2. Dry matter accumulation and light interception in pearl millet and groundnut as sole crops and as a one-row millet : three-row groundnut intercrop (means of 1978, 1979 and 1980).

efficiency with which intercepted light was converted into dry matter. In the sorghum/pigeonpea combination (Fig. lb), the intercrop was clearly able to combine much of the capacity of the sorghum to intercept light early in the season with at least some of the capacity of the pigeonpea to intercept it later. For each crop, however, the efficiency with which intercepted light was converted into dry matter was the same for intercropping as for sole cropping (Natarajan & Willey 1981b). Thus in this combination higher yields were achieved in intercropping because of greater light interception and not because of greater efficiency of conversion; in fact the combination displayed the classic 'temporal' complementarity of resource use that has traditionally been associated with combinations of early- and late-maturing crops.

In the millet/groundnut combination, although some temporal difference was observable between the crops, by the end of the season the total amount of light intercepted by the intercrop was virtually identical with that 'expected' from the interception patterns of the sole crops. Thus, in contrast to the sorghum/pigeonpea combination, the greater yield from intercropping was brought about not by greater interception but by greater efficiency of conversion. This effect has been ascribed to a better dispersion of light over a larger area of leaf in the intercrop, and perhaps to some complementary interaction between the C_4 millet and the C_3 groundnut canopies (Reddy & Willey 1981). Whatever the actual mechanism, this combination provides an excellent example of the kind of 'spatial' complementarity of resource use that can occur in intercropping.

As to the use of other resources in these two combinations, there-is some increase in the extraction of water from the soil profile compared with the sole crops and an improvement in total water-use efficiency because a greater proportion of the evapotranspiration passes through the crop as transpiration instead of being lost as evaporation from the soil surface (Natarajan & Willey 1981b, Reddy & Willey 1981). In recent experiments with millet/groundnut there is also some evidence of a greater production of dry matter per unit of water transpired. For nutrient use the pattern has been identical for both combinations in that any increase in yield over sole cropping is associated with an equal increase in nutrient uptake (Natarajan & Willey 1981b, Reddy & Willey 1981); for this resource, therefore, it seems likely that there will prove to be some situations where higher yields from intercropping will have to be at least partly paid for by greater fertilizer inputs.

A further aspect of resource use that is of considerable interest is how the advantages of intercropping are affected by the availability of resources. Because of our commitment to the semi-arid tropical regions of the world, our ICRISAT studies have concentrated on the effects of nutrient and/or moisture stress. For the nutrient effects we have consistently observed rather greater intercropping advantages where fertility is lower, and this has also been reported by other workers (IRRI 1975). But the effects of moisture stress have proved particularly spectacular. During the last three summer seasons we have been examining this by arranging treatments at different distances from a 'line source' of closely spaced irrigation sprinklers; this technique allows a wide range of moisture conditions to be examined on a relatively small area. Results with a combination of one row sorghum : two rows groundnut are shown in Fig. 3. In well-irrigated plots yields were very high but with increasing moisture stress they decreased to a level typical of many farms in semi-arid tropical regions. But for each crop the relative intercrop yield (i.e. intercrop yield expressed as a proportion of sole crop yield) increased with increasing stress (Fig. 3b) and thus the overall relative

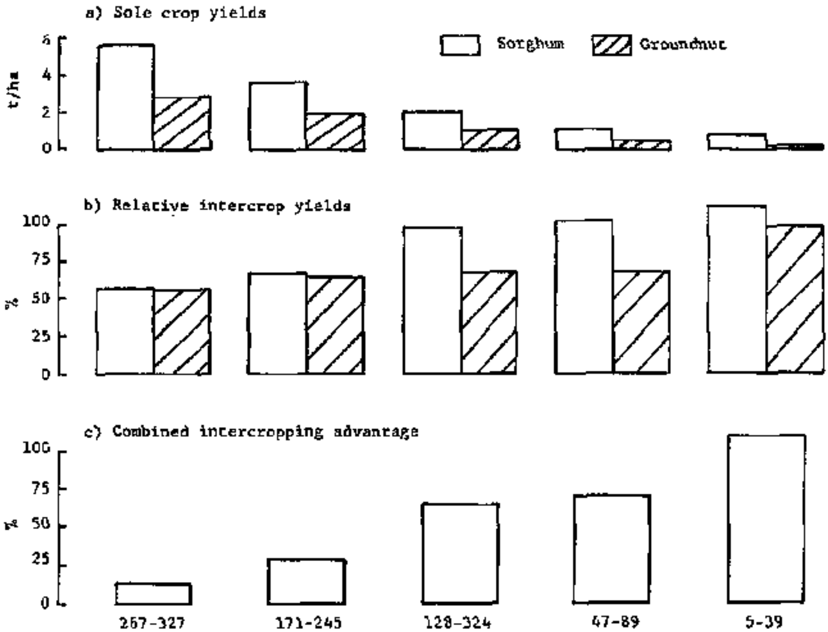

FIG. 3. Effect of moisture stress on sorghum and groundnut as sole crops and as a one row-sorghum : two-row groundnut intercrop (means of 1980, 1981 and 1982). Numbers below columns in c) represent the water applied (mm) through 'line source'.

advantage of intercropping also increased (Fig. 3c); where stress was greatest the advantage was a very considerable 109%.

Legume benefits

A combination of a legume with a non-legume is probably the commonest type of intercropping that occurs with annual crops and it has often been assumed that the presence of the legume must provide a net nitrogen benefit to the system. Usually this benefit has been thought of as a transfer of fixed nitrogen to the crop actually growing with the legume, though in fact the transfer concept also applies where fixed nitrogen is utilized by a subsequent crop.

There is of course considerable justification for the belief in this beneficial effect. The contribution of legumes in perennial "pasture systems is well authenticated and it was shown many years ago in pot studies (Nicol 1935, Virtanen et al 1937) that even over a short growing period a legume could excrete nitrogen that benefited an associated non-legume. Moreover, considerable residual benefits can accrue from annual legumes when grown as sole crops. It must be emphasized, however, that quantitative information from annual intercrop systems under field conditions is still very limited, and there are several factors to be considered when one tries to extrapolate from other situations.

An ICRISAT experiment specifically designed to quantify nitrogen benefits examined rainy season intercrops of maize/groundnut. Sole maize was grown as two rows 75 cm apart on a bed 150 cm wide. The same plant arrangement was maintained in intercropping to avoid confounding intercropping effects with population or spacing effects (Willey 1979); the groundnut was added as two intervening rows. Four different amounts of nitrogen were applied to the maize (0, 50, 100 and 150 kg/ha) in both sole cropping and intercropping. Residual effects were examined on a post-rainy season crop of sorghum to which four different amounts of nitrogen (0, 40, 80 and 120 kg/ha) were also applied, to allow any benefit to be quantified in terms of an equivalent amount of applied nitrogen. Treatments were continued on the same plots for three years.

With no nitrogen added, the sole maize crop was relatively poor, with a mean yield of 2.19 t/ha for the three years (Fig. 4). Adding a groundnut intercrop gave a good yield of groundnut (1.17 t/ha, or 59% of the sole crop) but depressed maize yield by 23%. However, the addition of the groundnut increased the yield of the following sorghum crop by a mean of 461 kg/ha or 17%. This was estimated to be worth about 20 kg/ha of applied nitrogen to the sorghum, When nitrogen was applied to the maize, sole crop yields were good (5.92 t/ha for means of 50, 100 and 150 kg/ha) and intercrop yields were virtually identical (5.90 t/ha), showing no net effect of adding groundnut; in contrast, the yield of groundnut was much suppressed (0.46 t/ha, equivalent to only 23% of the sole crop) because of greater competition from the maize. There was no evidence of any residual benefit from the intercrop groundnut in these treatments that had nitrogen applied; the mean sorghum yield after the sole crops was 3.367 t/ha and after the intercrops it was 3.343 t/ha.

These results illustrate some important general points. First, even when legume growth is good nitrogen does not necessarily benefit the associated non-legume, and indeed there can be a net reduction in yield because of competitive effects. An important factor here is probably the relative growing period of the two crops, and there are some indications from other experiments (Agboola & Fayemi 1972, Nair et al 1979, Yadav 1981) that benefits to an associated non-legume are more likely to occur with early-maturing legumes that release some nitrogen sufficiently early to allow the non-legume to respond; with later-maturing legumes benefits are only likely to be expressed as a residual effect on subsequent crops. Second, the results

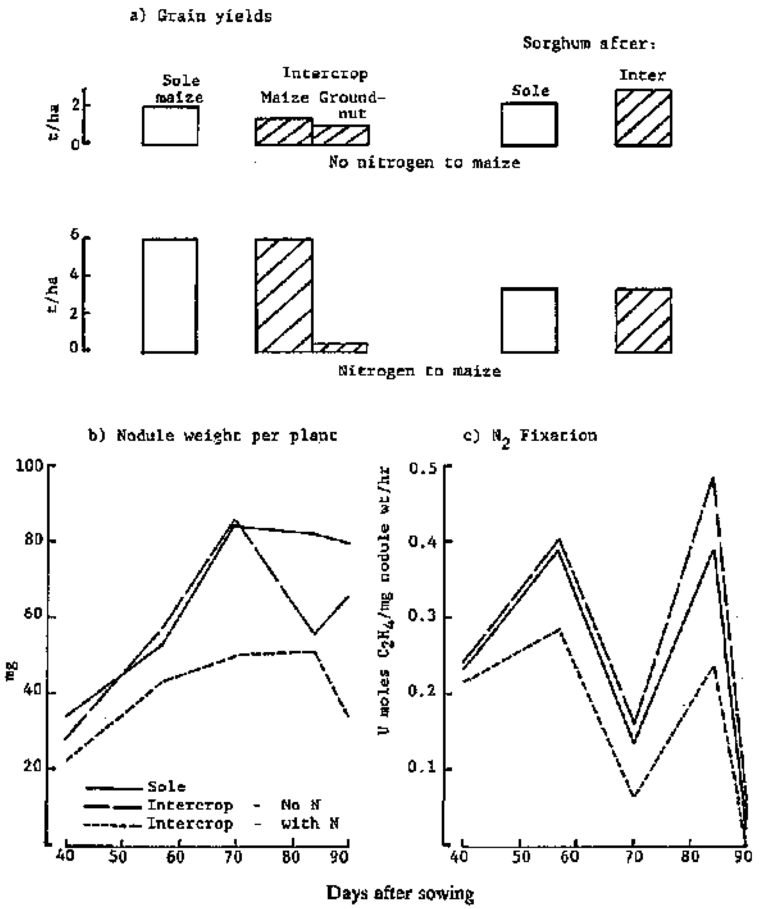

FIG. 4. The effects of a groundnut intercrop on an associated crop of maize and a following crop of sorghum: (a) seed yields, (b) groundnut nodule weight per plant, (c) groundnut N_2 fixation.

indicate that if there is poor legume growth, for example because of suppression by good non-legume growth, then potential benefits are likely to be very small. This point is emphasized by more detailed ICRISAT studies on nodulation and fixation rates. In the above maize/groundnut study, for example, the application of nitrogen to the maize reduced not only the nodule weight per plant but also the rate of fixation per unit of nodule weight (Nambiar et al 1983). Even more striking were some measurements made in the millet/groundnut studies described earlier: these showed that even where intercropping did not reduce the yield of groundnut dry matter per plant it still markedly reduced the rate of fixation (Nambiar et al 1983). These effects have been largely ascribed to the shading effect of the cereal and the fact that a reduction in photosynthesis may affect fixation more readily than growth. But whatever mechanisms are involved, these results suggest that intercrop legumes may sometimes fix less nitrogen, and thus make greater demands on soil nitrogen, than might be supposed from analogies with sole crops. Much more quantitative information is obviously required about this. Until this information becomes available, the potential nitrogen benefits of legume intercrops may have to be viewed fairly cautiously.

It must be emphasized at this stage that even when some of the nitrogen fixed by intercrop legumes is utilized by other crops, this is not necessarily an advantage for the intercropping system *per se.* Strictly speaking, intercropping is only advantageous if the nitrogen benefit is greater than in some alternative sequential system where sole legumes are followed by sole non-legumes. In developing countries where the legume is commonly grown only as a 'bonus' crop (e.g. the sorghum/pigeonpea combination described earlier), any fixed nitrogen that is returned to the system is presumably a net benefit in the same way that any legume yield itself is a benefit. Conversely, where the farmer's objective is to grow a balanced proportion of both crops (e.g. the millet/groundnut system described above), the possibility of lower fixation rates in intercropping suggests that the net nitrogen benefit could be greater in a sole crop sequence. But of course there may be other considerations: where leaching is a probem it may be beneficial to have another crop growing with the legume so that released nitrogen is taken up straight away; or, on a more practical level, if a farmer is growing disproportionate amounts of legume and non-legume the easiest way of dispersing any nitrogen benefit uniformly across the non-legume may be to distribute both crops over the same land area.

Control of weeds, pests and diseases

It is often claimed that traditional intercropping systems give better control over weeds, pests and diseases. While there is increasing evidence that this can be so, it must be appreciated that intercropping is an almost infinitely variable, and often complex, system in which adverse effects can also occur.

Weed growth basically depends on the competitive ability of the whole crop community, which in intercropping largely depends on the competitive abilities of the component crops and their respective plant populations. Broadly, where the total intercrop population is higher than in sole crops (which is very often the case), then greater weed suppression can be achieved (Moody & Shetty 1981, Rao & Shetty 1977); but where the total population is similar to that of the sole crops, weed suppression is likely to be some simple average of the two sole crops, taking into account their respective proportions. There can be considerable variation on this, however; thus in the sorghum/pigeonpea intercrop, even though the pigeonpea population is 'additional' to the sole sorghum population, overall suppression of weeds may be poorer than in sole sorghum if the slow-growing pigeonpea is confined to separate rows that are less competitive than sorghum rows. On the other hand, because of the additional total dry matter and leaf area index achieved with millet/groundnut, this combination may give better weed suppression than might be expected from its simple sown proportion.

For pests and diseases, the most commonly quoted effect is that one crop can provide a barrier to the spread of a pest or disease of the other crop; classic examples are the use of a cereal barrier to reduce insect attack on cowpeas in West Africa, or to reduce the insect-borne rosette and bud necrosis diseases in groundnuts. A particularly intriguing example of this kind has been studied at ICRISAT for three consecutive years. In this, a sorghum intercrop markedly reduces the incidence of the very widespread soil-borne wilt disease *(Fusarium udum)* of pigeonpea (Fig. 5). The remarkable aspect

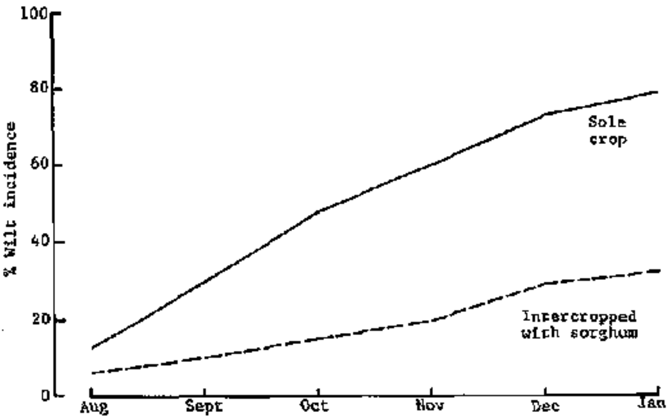

FIG. 5. Build-up of wilt disease (*Fusarium udum)* in sole and intercropped pigeonpea (means of 1979, 1980 and 1981).

of this effect is that it occurs even where pathogen levels in the soil are already high and the simple barrier mechanism does not provide a very plausible explanation. One possibility is that the sorghum roots produce some specific exudate that helps to reduce vigour or population, or both, of the pathogens; this is to some extent borne out by the fact that a similar barrier of maize appears to have less effect. But further information on this must await more detailed research.

The sorghum/pigeonpea also provides an excellent example of the possible complexity of the effects of pests (Bhatnagar & Davies 1981). Probably the worst pest of pigeonpea is a pod borer (*Heliothis* sp.) and this is also a serious 'headworm' of sorghum. In the intercrop, the *Heliothis* first builds up on the sorghum but is accompanied by some hymenopteran egg parasites that give an important measure of control. After sorghum harvest, the *Heliothis* transfers to the pigeonpea which is usually at the very susceptible early-flowering stage. Unfortunately, the hymenopteran parasites do not transfer and the natural parasite population is mainly dipteran larval parasites that are less effective. The net effect of these interactions between the pest and its parasites seems to be that pigeonpea as an intercrop may suffer greater pod-borer damage than as a sole crop.

Yield stability

Improved yield stability is a further feature that has often been claimed for traditional intercropping systems, though this claim has been based not so much on actual evidence as on the fact that some sound mechanisms for stability can be formulated. Two such mechanisms are the better control of pests and diseases and the greater relative advantages under stress that have just been referred to; where these occur, they can provide a useful buffer against low yields in adverse years. A third mechanism, and perhaps the most universally applicable one, is that if one crop fails, or grows poorly, the other can compensate; such compensation clearly cannot occur if crops are grown separately.

Until recently, evidence for greater stability was scarce and often subjective. Jodha (1981) showed that in India intercropping is often associated with erratic rainfall/high risk environments, while Norman (1974) found that in northern Nigeria farm incomes were less variable where there was greater reliance on intercropping, Trenbath (1974) reviewed a number of experiments but found little evidence of any meaningful increase in stability, though this may have been because the component crops were usually quite similar, A recent ICRISAT study has. examined stability across 94 experiments on sorghum/pigeonpea (Rao & Willey 1980) in a wide range of semi-arid environments in India, with rainfall varying from 406 mm to 1156 mm and sole crop yields varying from 310 to 6200 kg/ha for sorghum and 274 to 2840 kg/ha for pigeonpea. Several analyses were tried but the most striking was an estimation of crop 'failure', where this was taken to be where monetary returns fell below some required level. Fig. 6 shows that for any required monetary return per hectare the sole crops failed much more often than the intercrop. If a return of 1000 rupees (about US $110) is taken as an example, sole pigeonpea failed one year in five and sole sorghum one year in eight, but the intercrop failed only one year in thirty-six.

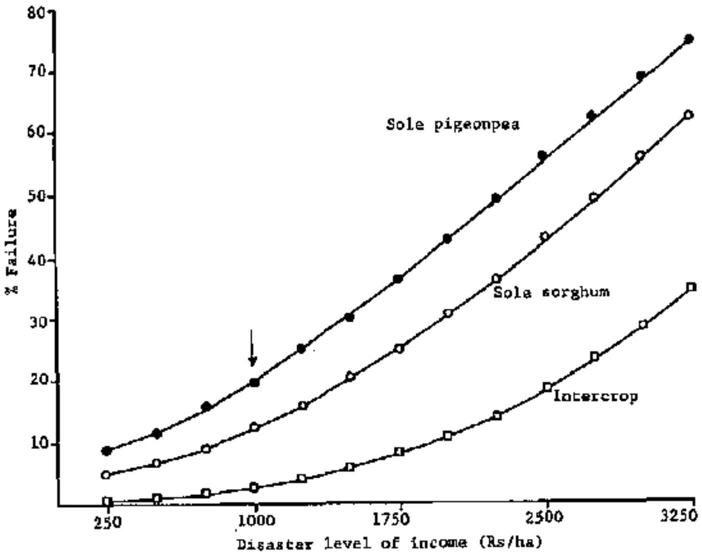

FIG. 6. Yield stability of sorghum and pigeonpea in sole cropping and intercropping: the probability of crop failure (after Rao & Willey 1980).

Intercropping in developed situations

There are many reasons why intercropping may be particularly appropriate for the small farmer in the developing areas of the world: the possibility of better pest and disease control, greater relative advantages under conditions of moisture and/or nutrient stress, and improved yield stability are all especially beneficial in the low-input/high-risk environment of most developing areas. But in more developed areas two basic questions need to be asked.

The first is whether the potential biological advantages are still sufficiently worthwhile. In fact this has been partly answered already by the examples given above. In the growth studies in particular, the sorghum/pigeonpea and millet/groundnut combinations had high populations, high inputs, improved genotypes and good management; as seen, yields were very high and intercropping advantages were considerable. This is also true of many intercropping experiments being reported now; indeed an early intercropping programme that showed very large yield advantages had the specific objective of studying high input in a good rainfall environment (Willey & Osiru 1972). It has already been pointed out, of course, that the relative advantages can be less with high inputs, but even a 10-20% advantage, which is modest for many intercropping combinations, can still be a worthwhile absolute increase when yields are high.

The second question is whether the intercropping system presents too many problems of practical management where agriculture is more developed; the problems usually suggested are sowing, the use of sprays or fertilizers that have to be different for different crops, and harvesting. The extent of these problems depends largely on the degree of mechanization. Where everything is done with hand tools, or with only simple machinery, there are few problems even where other production practices are highly developed. But with more sophisticated machinery, problems undoubtedly can occur. An important point to bear in mind, however, is that intercropping does not have to be the haphazard mixture of several crops that so often seems to be imagined: it can equally easily be, and often is, an orderly arrangement with different crops in separate rows. In this situation it is not difficult to envisage machinery 'directing' seeds, fertilizers and sprays to appropriate rows. Harvesting is likely to remain the real problem, though again conditions can be envisaged in which, for example, a tall seed crop can be combine-harvested over the top of a low-growing, later-maturing crop; and there are still simpler possibilities where the different crops are forage-harvested, or even grazed, together.

In summary, intercropping will only be a worthwhile system in developed conditions if the extra benefits it provides more than offset any extra difficulties it presents. But to balance this equation it may be necessary to take a broader view of the potential benefits than has been done so far. For the farmer a major benefit may be that intercropping provides a further option among cropping systems and, above all, a means of introducing a wider range of crops. Where greater diversity of cropping is desirable, therefore, the intercropping system deserves particular consideration.

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DISCUSSION

Finney: How do you decide the inputs to this system? Is the aim to maximize total productivity using the latest technology or to use the inputs and techniques that are locally available in the best way?

Willey: A bit of both. We are especially concerned with the small subsistence farmer who has few inputs; hence our emphasis on moisture stress and low fertility conditions in our trials. But there can also be advantages of intercropping under high input conditions. The system should simply be seen as one of the options to be considered in any given situation.

Spedding: You mentioned that in dry conditions a mixture of sorghum and groundnut might be exploring different horizons as their sources of water. Is that because the legume doesn't require a nitrogen supply and is thus able to explore deeper water sources which may be deficient in nitrogen? The sorghum would then benefit from the lack of competition for nitrogen in the water layers where nitrogen is available.

Willey: We had not thought of this but it seems a possibility.

Spedding: In British grasses a drought reduces growth because there is a shortage of nitrogen in the water that is available.

Karikari: In traditional intercropping systems in West Africa the crops are not planted all at the same time. What is the practice in India?

Willey: Different times of planting are an important device that the farmer can use, usually to increase the degree of temporal complementarity between crops. For example, in West Africa the farmer often sows millet with the first showers and groundnut two or three weeks later when the rains are more assured; this extends the total growing period and makes greater overall use of resources. In contrast, the Indian farmer nearly always uses some kind of animal-drawn equipment and it is much easier for him to sow both crops at the same time.

Scowcroft: Is there a genotypic component in the performance with intercropping? Will certain cultivars do better in intercropping than others, and can you start to select for the cultivars that perform better?

Willey: There can certainly be benefits from using the right genotypes. For example in sorghum/pigeonpea the shorter and early-maturing sorghum genotypes are ideal for intercropping with the pigeonpea.

Riley: In all your experiments the plants are sown in rows. Why do we plant crops in rows? Initially I suppose it was to assist weed control. Subsequently, with better drilling apparatus, this method allowed the stand of crops to be distributed evenly. Your experiments break the evenness of the stand so have you looked at whether the introduction of even greater randomness in the population leads to a greater or lesser benefit than simply having differences between rows?

Willey: It depends on the combination. In some combinations the plants have to be fairly close to each other if they are to get any kind of mutual benefit. With cereals it may be important to have fairly wide rows of the cereal and at least two or three rows of the other species. Our experimental row arrangements are typical of Indian farming where the farmer uses animal-drawn equipment.

Haq: Have you used any other legume such as chickpeas or rice bean with sorghum or maize?

Willey: We have used chickpeas quite a lot. In the central parts of India chickpea is growing at temperatures a little higher than its ideal environment and we can get a small beneficial yield effect by shading with an intercrop.

Day: A further step in intercropping is to grow mixtures of varieties of the single crop. Martin Wolfe has been exploring this in relation to the control of leaf diseases in cereals, using three-component mixtures of varieties of barley and of wheat. In the absence of powdery mildew, which the mixture is really designed to combat, he gets increases in yield of from 2 to 8%. This introduces spatial diversity of the sort that Dr Riley was suggesting. Would this be a possible avenue to pursue in the developing countries?

Willey: It is not very surprising that mixtures within a crop have given only small increases in yield in the absence of disease. Increased yield depends on some degree of complementarity between crops and there is most likely to be complementarity where crops are quite different.

Rudd-Jones: I think the principle of Martin Wolfe's mixtures was different (to that of intercropping). For example, in 1967 a new race of yellow rust appeared in the UK and crops of one wheat variety had to be ploughed in because the losses were so serious. Where an obligate pathogen has a very narrow host range there are advantages in mixing varieties to reduce losses from disease when the resistance of a particular variety breaks down. There is however a problem in harvesting such a mixture of varieties since they may mature at different times or may differ in composition.

Plaisted: In a few parts of the world where potatoes are the major item of food a mixture of varieties is often grown. I think that is because people like a mixture of flavours when they eat 6 or 7 kg a day.

Cooper: The intercropping combinations you mentioned were all cereals plus legumes. Are mixtures of two cereals or two contrasting legumes also successful?

Willey: We have looked at the groundnut/pigeonpea combination and this can produce as much as an 85% groundnut crop plus an 85% pigeonpea crop. Cereal/cereal combinations are commonly grown, probably because of improved stability.

Bingham: In allelopathy the growth of one species adversely affects the growth of another. Have you identified any allelopathic relationships among your crops?

Willey: Among the many combinations now examined in intercropping research there seem to be surprisingly few harmful ones. Even if there is no advantage, there is not often a genuine disadvantage. We have had allelopathic effects in sequential cropping systems where sorghum has reduced the yield of subsequent crops.

Finney: Could you comment further on the potential of intercropping in agriculture in developed countries?

Willey: The main place for it is in the developing countries. The improved stability and particularly high advantages under stress conditions point to the small and low input farmer. But if we are considering better use of resources intercropping is potentially a universally applicable system. An intercrop grown in rows is a well-organized crop that farmers in the developed world can potentially handle. There are management problems of course, so we have to consider in any given situation whether there are sufficient advantages to outweigh these problems.

Finney: With high and specialist input systems in the developed world designed for individual crops it might be very difficult to introduce intercropping. Herbicide and fertilizer programmes, for example, are geared to particular crops.

Willey: I don't see why fertilizer should be a problem. Both crops usually want phosphorus and potassium, so these can be applied as basal dressings. The main difference is usually in nitrogen requirement but this can be directed to the rows of the crops that need it.

Zadoks: In the Netherlands sowing wheat and barley with legumes or grass is fairly common practice again. Oats and barley used to be grown together on sandy soils. This practice disappeared but now we are talking about it again. Mixtures of wheat and barley, or wheat, barley and rye have been popular for centuries in western Europe and may be reappearing in the developed countries.

Hegarty: Have any problems developed with soil erosion in your intercropping experiments? Have you found it necessary to consider zero tillage methods?

Willey: We haven't looked at this but one of the advantages of temporal mixtures is that they provide ground cover for longer and therefore erosion is less likely.

Hymowitz; Is all harvesting done by hand in the experiments you described? Would there be any losses if wagons or tractors were used?

Willey: The kind of farmers we are talking about are committed to harvesting by hand, though they may have threshing machines. Harvesting might be a problem in developed countries but I believe that if farmers thought they would benefit sufficiently from intercropping they would devise harvesting methods for dealing with two crops.

Bell: You mentioned that sorghum might exude materials that affect pathogens on the pigeonpeas. Do you know of any differences in the effects of light sorghums and dark sorghums? One of them has a high content of tannins and phenolics and these might affect the pests.

Willey: That is a useful idea that would be worth examining further.

Rudd-Jones: That effect would be indirect. The disease control might be due to a microbial antagonist which was stimulated by the root exudate.