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EVALUATION AND PRESENTATION OF INTERCROPPING ADVANTAGES

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SUMMARY

It is proposed that two distinct objectives should be recognized in the evaluation of intercropping advantages: (i) a biological objective to determine the increased biological efficiency of intercropping and (ii) a practical objective to determine the advantages that are likely to be obtained by a farmer. The sole crop systems with which intercropping must be compared to satisfy these objectives are defined. Evaluation in relative, absolute, monetary and nutritional units is discussed and some aspects of presenting intercropping data in graphical form are illustrated.

One of the more problematic areas of intercropping research is the quantitative evaluation of the advantages provided by any given intercropping system. The major difficulties appear to be identifying the sole crop systems with which intercropping should be compared and deciding on the terms, or units, in which advantages should be measured. This paper tries to show that these difficulties might be simplified by recognizing two distinct objectives in the evaluation process. The first is a basic biological objective that attempts to answer the question 'What is the increased biological efficiency of a given intercropping situation compared with sole cropping?' The second is a practical objective and attempts to answer the question 'How great an advantage, compared with sole cropping, is a given intercropping situation likely to provide in farming practice, taking into account the crop requirements and practical constraints of the farmer?'

The paper reviews a number of methods of examining these two objectives, considering both the evaluation process itself and the presentation of data in graphical form. It considers only two-crop intercropping; this is admittedly the simplest intercropping system but it is also the most widespread.

THE BIOLOGICAL OBJECTIVE

Comparative sole crop systems

The biological efficiency of intercropping is determined by comparing the productivity of a given area of intercropping with productivity if the same area were to be divided between sole crops to give the same ratio of the two crops

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as in intercropping. Maintaining the same ratio of the two crops across this comparison is essential to avoid biases that can favour either the intercropping or the sole cropping system. Moreover, this ratio must be expressed in terms of actual production and not initial sown proportions. Consider for example two crops, A and B, that have sole crop yield potentials of 3000 and 1000 kg ha^{-1} and which in an intercropping system of 50:50 sown ratio (e.g. alternate rows) produce 2250 and 250 kg ha^{-1}, respectively. If total intercropping productivity (i.e. 2250 + 250 = 2500 kg ha^{-1}) is compared with total productivity from a 50:50 sown ratio of sole crops (i.e. 1500 + 500 = 2000 kg ha^{-1}) the intercropping system appears to be more efficient; this is the comparison that was often made in earlier intercropping work. But in fact the exact intercropping yields of both crops could be produced from 0.75 ha of sole A and 0.25 ha of sole B. Thus in the sense that intercropping does not produce any more yield than can be equally easily produced from the same total area of sole crops, it does not offer any genuine improvement in efficiency over sole cropping.

This apparent contradiction arises because in this particular example crop A is the more competitive component in intercropping and it also has the higher sole crop yield potential. Thus comparison with a sole crop system of the same sown ratio favours the intercropping system because competition in the intercropping system results in a higher proportion of the higher yielding crop (in effect a 75:25 yield ratio in the intercropping system is being compared with a 50:50 yield ratio in sole cropping). Conversely of course, if the more competitive crop in intercropping has the lower yield potential this comparison on sown ratios favours the sole crop system. It is this kind of bias that is avoided by basing the comparison on a division of the sole crop area that produces the same ratio of yields as in intercropping (e.g. the 75:25 ratio in the above example).

It will be appreciated, however, that because it is impossible to predict precisely what the competitive effects and final yields will be in any given intercropping system, the ratio of sole crops with which intercropping must be compared can only be calculated retrospectively. Thus in the sense that this sole crop system is not a precisely known alternative to intercropping at the time of sowing (either for the farmer or the experimenter) it must be recognized as something of a hypothetical situation.

Units of measurement

To calculate biological efficiency the crop productivities can in fact be expressed in any units that provide a common base on which to combine and compare quite different crops. However, the general approach has been to use relative units, of which the simplest is relative yield. Thus for a situation where crops A and B give sole crop yields of 1000 and 2000 and intercrop yields of 750 and 1000, the relative yield of crop A in intercropping is 0.75 (i.e. 750/1000) and of crop B 0.50 (i.e. 1000/2000). Even though the crops may be of very different kinds, these relative yields can be added to form a relative yield total (or RYT, after de Wit and van der Bergh, 1965). More commonly, the land equivalent ratio has been the relative unit used. This is defined as the relative land area required as sole crops to produce the yields achieved in intercropping; it is in fact numerically identical to relative yield. Thus in this same example the individual crop land equivalent ratios (denoted La and Lb) are again 0.75 and 0.50 and the total land equivalent ratio (LER) is 1.25. Because of its common usage the LER is the unit used in this paper but an LER of say, 1.25, may be taken either as a 25% greater area requirement for the sole crop system or as a 25% greater relative yield for intercropping; either way, the figure indicates a 25% greater biological efficiency for intercropping.

Because LER is based on relative units, an actual calculation of LER does not need any conscious assumption about which sole crop system is being used for comparison; in effect, an intercrop LER value is simply compared with 1.0. It should not be forgotten, however, that this 1.0 represents unit area of sole cropping divided between the two crops to give the same yield ratio as in intercropping. In the above example, therefore, the 1.0 represents a sole crop ratio of 0.60A:0.40B, calculated from the intercropping yield ratios (A = 0.75/1.25 = 0.60; B = 0.50/1.25 = 0.40). As will be seen later, remembering this inherent assumption in the LER calculation is especially important when using some of the modifications of the LER concept, or when using other units of productivity.

Evaluation

When only two crops are involved LER values can be conveniently presented and examined in a two-way diagram (Fig. 1a) which shows both LER and its composition in terms of La and Lb. The increased biological efficiency of a given treatment is indicated by difference from the LER = 1 line at constant yield ratio (see examples indicated in Fig. 1a). It has been explained in more detail elsewhere (Willey, 1979) that this two-way diagram is also very useful for indicating competitive effects. Assuming that all six example treatments in Fig. 1a were sown at a 50:50 ratio, those points above the 'equal competition' line indicate that crop A was more competitive and those below that crop B was more competitive. If desired, this competition can be quantified by using the Competitive Ratio (CR): for example, a CRa value of 2 in Fig. 1a indicates that for a 50:50 sown ratio La was twice Lb and thus crop A could be regarded as twice as competitive as crop B (see Willey and Rao, 1980)

Although the LER (or relative yield) provides an ideal base on which to compare any crops, it is commonly criticized because it gives no indication of absolute yields. And indeed, even though the calculation of biological efficiency is not intended as a practical evaluation, it is reasonable to want to know at what yield level a given efficiency is being achieved. This problem can be largely overcome simply by providing the sole crop yields on which the LERs are based. It seems to be seldom realized, however, that it is possible to go one step further because the LER type of calculation can be carried out

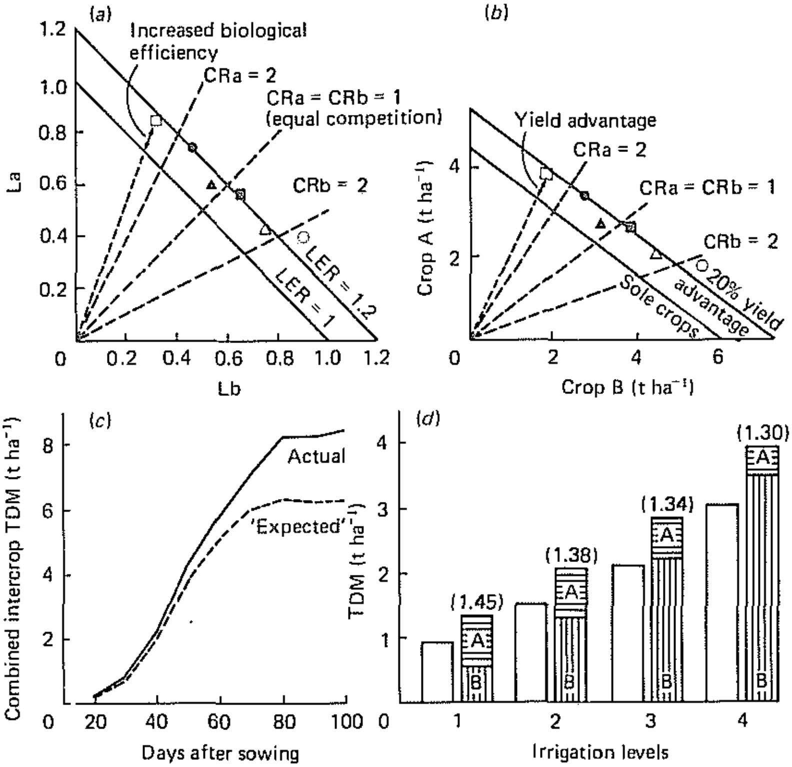

Fig. 1. (a) Two-way diagram of LERs illustrating increased biological efficiencies and competitive effects of six example treatments; (b) two-way diagram of the same treatments as in (a) using absolute yields; (c) actual and 'expected' yields for TDM accumulation in a millet/groundnut intercrop (ICRISAT data); (d) hypothetical data of actual (A, B) and 'expected' (□) yields for four irrigation treatments; LERs shown in parenthesis. (Treatments in (a) and (b): 1 = ●, 2 = ○, 3 = □, 4 = ▲, 5 = ■, 6 = △).

using absolute yields themselves provided the importance of constant yield ratios is recognized. The same six example treatments in Fig. 1a are shown again in Fig. 1b, assuming absolute sole crop yields of 4.5 t ha^{-1} for crop A and 6.0 t ha^{-1} for crop B. There is obviously some distortion of the symmetrical LER graph, but lines joining the two axes can be drawn to indicate biological efficiencies (now perhaps better termed potential yield advantages) and lines from the origin can still be drawn to indicate competitive effects.

A further way of using absolute yields to indicate potential intercropping advantages is to make a comparison with the yield 'expected' if there is neither an advantage nor a disadvantage from intercropping. In effect this is the equivalent, in absolute terms, of the LER = 1 situation which was described above and which represents a unit area of sole crops divided to give the same yield ratio as in intercropping. Thus for the earlier example where La was 0.75 and Lb was 0.50 the absolute expected yield would be that from a unit area divided into 60% sole A and 40% sole B. This approach may be especially useful when different intercropping treatments are being compared with different levels of sole crop yields, because the use of LERs obscures these differences in yield levels. To give two examples, Fig. 1c shows an expected growth curve for a millet/groundnut intercrop to illustrate the increased efficiencies that accrued during growth. Some hypothetical data from an irrigation experiment in which it is desired to examine yield advantages at each irrigation level are shown in Fig. 1d. LERs can also be added to these absolute yield graphs to give a more complete picture. With this addition, Fig. 1d would seem to be a convenient way of illustrating the potentially confusing but not uncommon situation where, because of increasing yield levels, a decreasing LER still results in increasing absolute yield advantages. Yields of the individual crops might also be included; in Fig. 1d these individual yields indicate the increasing yield ratio (and thus the increasing competitive ability) of crop B as irrigation increases.

THE PRACTICAL OBJECTIVE

Comparative sole crop systems

It was suggested elsewhere (Willey, 1979) that when considering a practical assessment of intercropping advantages there are three criteria that determine which sole crop systems should be used for comparison. An important underlying assumption of these criteria is that the farmer's objective may be more complex than a simple desire to maximize output. He may have to contend with various practical constraints that determine what amounts or proportions of the different crops he needs to grow; for example he may have to produce a certain balance of crops because of the need to spread the timing of inputs such as labour, or because of the desire to spread risk. Such constraints will apply of course whether the farmer opts for an intercropping or a sole crop system. It follows therefore that when evaluating a given intercropping system any practical constraints must be satisfied not only by the intercropping system itself but also by the sole crop system with which intercropping is being compared.

Stating the three criteria more broadly than was given earlier:

Criterion 1. Where any amounts or proportions of the crops are acceptable to the farmer. This criterion assumes that there are no constraints of the type outlined above. The farmer's aim is to maximize output and this could mean growing both or only one of the crops. Intercropping is thus logically compared with the most productive sole crop system, which must consist of growing only the higher yielding sole crop.

Criterion 2. Where some given yield ratio of crops is needed by the farmer. This criterion assumes both crops are needed, and in some desirable yield ratio. In this instance it is not valid to compare intercropping with the higher yielding sole crop because by definition growing only one of the crops is not an acceptable alternative. Comparison must be with a combination of the sole crops that also provides the required yield ratio.

Criterion 3. Where there is some constraint on the amount of one or both of the crops that is needed by the farmer. Earlier, the only situation recognized under this criterion was the need for a full yield of some critical crop (e.g. a staple food crop). The criterion is now broadened to recognize that this same kind of constraint may occur in more forms (see later). Intercropping is logically compared with the most productive sole crop system that also provides the required amount of one or both of the crops.

Units of measurement

The common approach when trying to make a practical evaluation of intercropping is to use units that are appropriate to the purpose for which the crops are being sown (e.g. monetary values for cash crops or nutritional values for food crops). But using such units does not in itself ensure a practical analysis unless the criteria given above are still taken into account. Conversely, provided the above criteria are recognized, a practical analysis can be carried out with a wide range of units. In the following sections evaluation is considered under the broad headings of *relative, absolute, monetary* and *nutritional* units.

Evaluation

Relative units. The LER is again used here to illustrate analyses with relative units. It was emphasized earlier of course that the main purpose of the LER is to determine biological efficiency, or potential yield advantage, and undoubtedly some of the major criticisms that have been levelled at the LER have arisen because it has been used in some practical context for which it is not appropriate.

Considering the three criteria in order, the LER is not appropriate for Criterion 1 because the LER removes any differences in absolute yield levels of the crops and such differences are necessary to establish which system gives maximum output. It is clear from the definition of Criterion 2, however, that this criterion makes exactly the same intercropping versus sole cropping comparison that is embodied in the LER; for this criterion, therefore, the LER can give a valid assessment of the relative yield advantage attainable in practice. However, there is an important reservation to this use of the LER. Mead and Willey (1980) have pointed out that if an LER is taken as the advantage achievable by a farmer, the assumption is that the ratio of yields in that LER is exactly that required by the farmer. Similarly, if an experimental analysis compares the LERs of several intercrops on an equal basis, the assumption is that all their different yield ratios are acceptable. Clearly the farmer may frequently require a rather different yield ratio from that generated by any given experimental treatment. Thus Mead and Willey (1980) showed that any required ratio could be achieved (and at least some of the advantages of intercropping utilized) by growing the intercrop on part of the land area and one of the sole crops on the remainder. The sole and intercrop proportional areas can be determined by first calculating the area (E) of the appropriate sole crop (assumed to be A) that would have to be added to 1 ha of intercropping. The relationship between the required yield ratio of A (p) and its additional sole crop area is most easily seen from the equation:

$$p = (La + E)/(LER + E) \tag{1}$$

Mead and Willey proposed the term 'Effective LER' (ELER) as a measure of the net advantage from the combined intercrop plus sole crop area. This ELER can be determined by adding the intercrop and sole crop relative yields from the proportional areas indicated by Equation 1, or it can be directly calculated:

$$ELER = Lb/[(1 - La) + (LER - 1)p] \tag{2}$$

The ELER must be less than the LER and it progressively decreases as the required yield ratio departs further from that produced by growing only the intercrop. Mead and Willey presented ELERs against required crop ratios and showed that they lay on shallow curves, as can be seen for two different intercrops in Fig. 2a. In this particular example, combining a sole crop with Intercrop 2 (which has the higher LER) is a better proposition than combining a sole crop with Intercrop 1 only if the required yield ratio is about 60% A or greater; thus, as can be seen, for a 50:50 required ratio Intercrop 2 retains a higher ELER.

An alternative way of presenting ELERs could be on a two-way LER diagram as shown in Fig. 2b. In this instance the ELERs are conveniently straight lines joining the intercrop points with the sole crop yields, and more information is evident on the LERs of individual crops than in Fig. 2a. Required ratios can be depicted by straight lines from the origin, as shown for the required 50:50 ratio; again the higher ELER of Intercrop 2 can be seen for this requirement. The proportional sole crop areas that would have to be combined with Intercrop 2 are also shown for illustrative purposes, though this presentation would be cumbersome for more than one intercrop.

Turning to the remaining Criterion 3, Reddy and Chetty (1984) showed how the Effective LER concept could be used to accommodate a situation where the farmer's basic requirement is to ensure a given amount, or a proportional yield, of a staple food crop. They showed that any such requirement could again be met by sowing part intercrop and part sole crop. The net advantage from the whole area they termed the Staple LER (SLER). When plotted against required amounts of one of the crops the SLER values fall on straight lines, as shown in Fig. 2c for the same two intercrops as in Fig. 2a; SLER values for a requirement of 70% of crop A are illustrated. As with the ELER, however, it could again be useful to indicate SLER values on a two-way diagram. The form of this diagram remains exactly the same as the two-way ELER one but SLERs are now indicated by horizontal (or vertical) lines (Fig. 2d); SLERs for a 70% yield of crop A are again illustrated.

In general, however, the concept of adjusting intercropping and sole cropping areas to satisfy some specific requirement seems to have found little favour as a

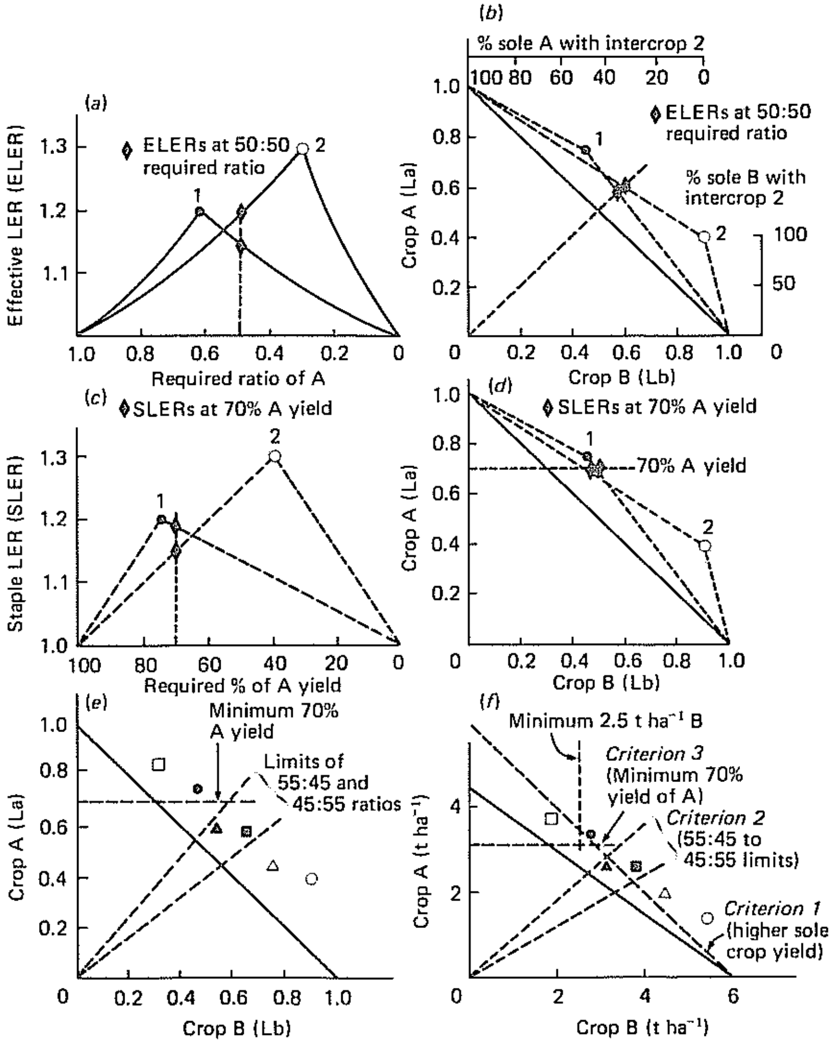

Fig. 2. (a) Effective LER (ELER) of two of the six intercropping treatments in Fig. 1 plotted against required ratios of crop A; (b) ELER of the same two intercropping treatments plotted on a two-way diagram; (c) Staple LER (SLER) of the same two intercropping treatments plotted against required % of crop A; (d) SLER of the same two intercropping treatments plotted on a two-way diagram; (e) concept of broad limits on practical requirements using LERs; (f) concept of broad limits on practical requirements using absolute yields. Symbols as in Fig. 1.

practical analysis among researchers. This may be because the concept is thought to be too theoretical, and yet farmers in the developing world who are typically growing several crops in a range of different systems must do some kind of balancing of production across their different cropping areas. But perhaps the real problem lies in the degree of precision implied in these analyses. It is obviously very desirable to recognize that a farmer may have certain crop requirements, but in practical terms these may have to be set within much broader limits. For example, when a farmer is thought to require equal proportions of the two crops, broad limits on yield ratios might be set from 45:55 to 55:45 instead of exactly 50:50. On this basis two of the six treatments illustrated in Fig. 2e would be acceptable; because both are acceptable, these two treatments might then be directly compared on their full LER values if desired. Similarly, instead of evaluating in terms of an exact 70% requirement of the staple food crop, as in the SLER example above, it might be more practical simply to identify treatments that satisfy at *least* this minimum food requirement. In this instance Fig. 2e shows that treatments 3 and 1 would be acceptable, and again these might be compared on their full LER values.

It is evident of course that other treatments might be brought within any broad limits by again adjusting with some sole crop area; if these adjustments were also viewed in broad terms they might be considered practicable.

Absolute yields. Absolute yields are the simplest practical measure of crop productivity and, provided the problems of different yield potentials discussed earlier are recognized, they can be used to evaluate any of the three Criteria. A particularly appropriate situation in which to use absolute yields may be when the crops are grown for different purposes, for example one as a cash crop and the other as a food crop. This situation has been completely ignored in practical analyses because of the desirability of having a common base on which to combine crops; monetary and nutritional analyses, for example, have invariably assumed either that both crops are cash crops or that both are food crops.

With different purposes for the crops, there will almost certainly be some constraints on crop requirements and Criterion 1 is unlikely to apply. Criterion 2 can be evaluated exactly as for relative yields, i.e. either for a specific crop ratio, or for broader limits. However, Criterion 3 can only be evaluated with an SLER type of analysis if yield above the required amount of 'staple' can be equated with yield of the other crop (e.g. if surplus food crop in a food crop/cash crop system is convertible into cash). But the 'minimum limit' concept could be used for any Criterion 3 situation and could be particularly useful when a surplus of one crop could not be equated with the other crop. Moreover, this limit concept has the advantage that limits could be set for both crops. Thus, in addition to a minimum food crop requirement (crop A) the farmer could have a minimum cash requirement represented by 2.5 t ha^{-1} of crop B; it can be seen from Fig. 2f that only treatment 1 would satisfy both these requirements. It is also worth emphasizing that these limits could take other forms and that an upper limit might occur. For example, in a food crop/cash crop system the farmer might not want a system that produces too much of the food crop if its surplus is not convertible to cash; similarly, he might not want too much of the cash crop if this introduces problems of handling and marketing.

Monetary units. The use of monetary units has always had considerable appeal in intercropping evaluation because of the obvious economic implications. Strictly speaking, monetary units should only be used when the crops are genuinely marketable cash crops, but such units have often been used simply

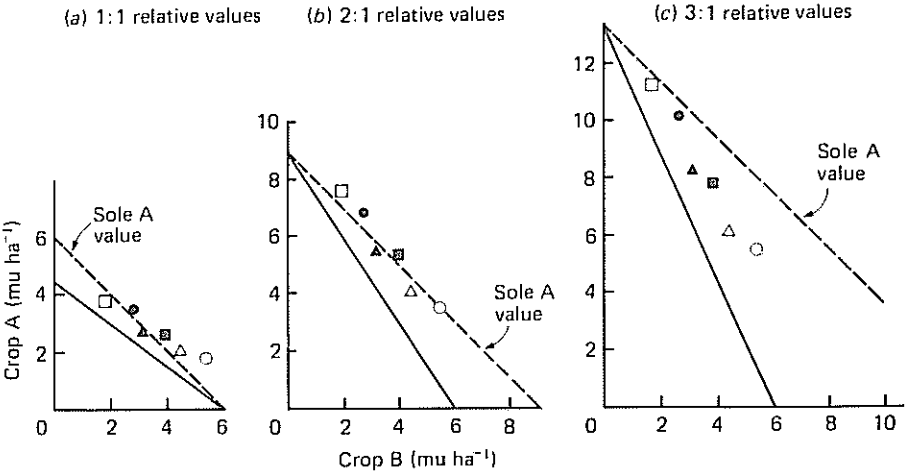

Fig. 3. Two-way diagrams showing the values of the six example treatments in Fig. 1 at different relative values of the two crops (mu = monetary units.) Symbols as in Fig. 1.

to provide the common base between crops; not surprisingly, possible biological and practical objectives have often been confused. Even when a practical evaluation has been implied, there has seldom been any recognition of the farmer's possible practical constraints and it has usually been assumed that the only requirement is for maximum monetary returns.

If there are genuinely no practical constraints, i.e. Criterion 1 applies, then a monetary analysis is conceptually very straightforward. All sole or intercrop situations are valid practical alternatives and can be compared on the basis of their total cash value. It follows that intercropping is only advantageous if it exceeds the value of the higher value sole crop. Changing market values can be taken into account by considering different ratios of values of the two crops. A relative increase in the value of a given crop progressively favours those systems that have higher proportions of that crop. An example is shown in Fig. 3, where at a 1:1 relative value treatment 2 has the highest returns (basically because of its high LER); however, at a 2:1 relative value treatment 1 exceeds treatment 2 because of a higher proportion of the higher value crop (now crop A), and at 3:1 growing sole A becomes the best proposition. Francis and Saunders (1983) have stressed that this kind of analysis can be useful not only to examine a particular data set, but also to predict what treatments or systems are likely to be most worthwhile given certain price ratios or yield levels.

Where practical constraints on crop requirements do occur, and Criterion 2 or 3 applies, analyses have to follow the same patterns as outlined for relative or absolute yield above. Monetary benefits are then logically expressed as the increase in value of the intercropping system compared with the appropriate sole crop system. Thus for Criterion 2 the benefit would be the value of intercropping less the value of separate sole crops giving the same yield ratio as in intercropping. Willey (1979) termed this the Monetary Advantage (MA); it can be directly calculated from the values of the intercropping and sole cropping situations defined above or, given that LER values are probably already available, it can be very simply calculated as:

$$\text{MA} = \text{Value of intercrop} \times (\text{LER} - 1)/\text{LER} \qquad (3)$$

In effect of course the MA simply expresses the relative advantage indicated by the LER as an absolute monetary advantage. Thus, given that Criterion 2 applies, an LER of 1.25 indicates not only a relative yield increase of 25% but also a monetary increase of 25%.

Like the LER calculation itself, this calculation of MA assumes that the ratio of crops in the intercropping system is exactly that required by the farmer. For different requirements the concept of adjusting with a sole crop area could again be used if desired. Thus an Effective Monetary Advantage (EMA) could be calculated equivalent to the ELER where a different ratio is required. Following the pattern in Equation 3 this could be calculated as:

$$\begin{aligned}\text{EMA} = {} & (\text{Value of unit area of combined intercrop and extra} \\ & \text{sole crop}) \times (\text{ELER} - 1)/\text{ELER}\end{aligned} \qquad (4)$$

Similarly, for Criterion 3 an SMA could be calculated equivalent to the SLER; the calculation would be exactly as in Equation 4 but with SLER substituted for ELER.

But these adjustments with sole crop areas to produce EMA or SMA have the same problems discussed earlier for the ELER and SLER. Following the simpler approach of setting broader limits, therefore, a more practical evaluation might be a direct comparison of total values, given that for Criterion 2 the systems are within acceptable crop ratio limits and that for Criterion 3 they satisfy the necessary minimum (or maximum) requirements.

Nutritional units. Evaluation has often been carried out in nutritional units and these are meaningful in subsistence situations where the crops will be eaten by the farmer and his family. As with monetary analyses, it has commonly been assumed that the farmer's aim is simply to maximize output (i.e. Criterion 1). It can be argued, however, that, particularly in subsistence situations, a farmer may experience practical constraints on what he grows because he cannot meet requirements by selling some crops and buying in others. Criteria 2 or 3 may thus apply and analyses should then follow identical patterns to those outlined above.

One of the problems with nutritional analyses, however, is that the intercropping system which is best for one nutritional requirement (e.g. calories) may not be best for another (e.g. protein). Beets (1982) concluded from a maize/soya experiment that a farmer would have to grow sole maize for maximum output of calories, intercrops for crude protein or methionine, and sole soya for lysine. Trenbath (1982) contended that subsistence crops would at

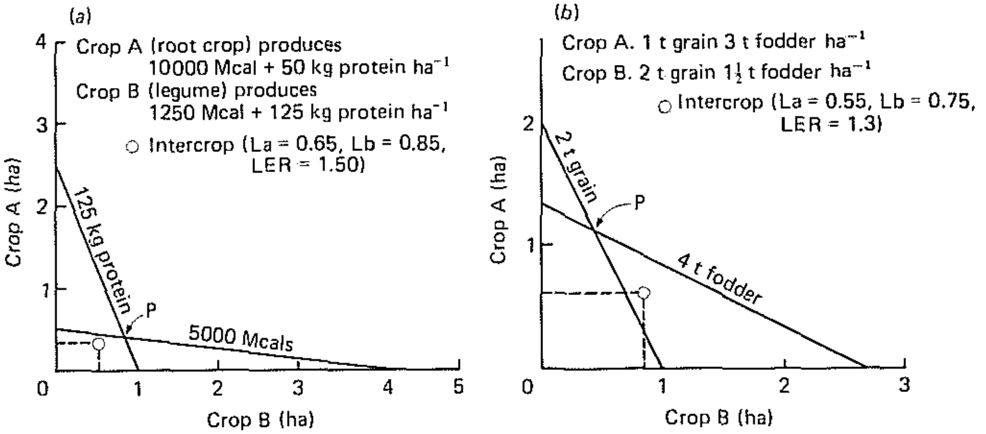

Fig. 4. Examples of minimum land areas required to produce two simultaneous requirements from sole crops or an intercrop. Requirements are (a) 5000 Meals and 125 kg protein, and (b) 2 tonnes of grain and 4 tonnes of fodder.

least have to satisfy the calorie and protein requirements simultaneously. He outlined an approach to determine the desirable balance of these two factors. Instead of yield per unit area, Trenbath preferred the concept of minimum land area required to produce a given food need because he argued that any yield advantage for subsistence crops would be seen as an opportunity to cultivate less land (or perhaps to divert more land to cash crops).

Trenbath suggested how minimum land areas could be depicted on a two-way diagram as shown in Fig. 4a. The diagonal lines represent the areas required to produce either the protein or the calorie requirement if the land area is divided between sole crops. In this example it is assumed that one crop is a root crop (crop A) producing 10 000 Mcals and 50 kg protein ha^{-1} while the other is a legume (crop B) producing 1250 Mcals and 125 kg protein ha^{-1}: the annual food requirement of the farmer's family is taken as 5000 Mcals and 125 kg protein. If one crop has a higher calorie production per hectare and the other a higher protein production, the lines on the two-way diagram cross. The ratio of sole crops that exactly meets both caloric and protein requirement on the least land area is obviously point P, which can be determined by setting up two simultaneous equations (Federer, 1983; personal communication): thus if x and y are the required areas of crops A and B, respectively, then requirements can be written for calories, 5000 = 10 000x + 1250y, and for proteins, 125 = 50x + 125y. These required areas work out at 0.40 ha of crop A (x) and 0.84 ha of crop B (y), making a total of 1.24 ha.

Assuming now an intercrop with an LER of 1.5, made up of 0.65 for crop A and 0.85 for crop B, the least area that would ensure the minimum requirements of both calories and protein would be 0.9 ha (giving 6810 Mcals and 125 kg protein). This point can be represented on the two-way diagram by plotting the 0.9 ha in the ratio of the individual LERs (i.e. 0.39 ha and 0.51

ha). The point must represent a total area less than that of point P (as in this example) for the intercrop to be advantageous. In this instance 0.9 ha of intercrop compares with 1.24 ha of sole crops so 38% more land would need to be cultivated as sole crops compared with intercrops.

To carry this analysis one step further, this particular example suggests that growing only the intercrop is not particularly efficient because there has to be a considerable surplus of calories to ensure enough protein. Again the concept of growing some area of intercrop and some area of sole crop can be adopted to provide just the right requirement of each. Trenbath suggested that a linear programming technique could be used to calculate the sole and intercrop proportions. The calculations can also be done on the basis of yield ratios using the Effective LER approach (Equation 2) because the required yield ratio must be that at point P in Fig. 4a. For crop B, the crop that has to be increased, the required ratio is 0.84/1.24, i.e. 0.68. For Equation 2:

$$0.68 = (0.85 + E)/(1.5 + E)$$

So E is 0.53. Thus 0.53 ha of sole B would need to be grown with 1 ha of intercrop to give the right ratio of the two crops, but this would provide 64% more than the requirement. The minimum land area resolves to 0.61 ha of intercrop and 0.32 ha of sole B, i.e. a total of 0.93 ha.

This example illustrates the greater complexity of adjusting for two factors because the adjusted area of intercrop plus sole crop is actually greater than the original intercrop area itself. This occurs because the intercrop provides a greater amount of protein (138.5 kg ha^{-1}) than the high-protein sole crop (125 kg ha^{-1}). Presumably in this instance the farmer would prefer to grow only the intercrop even if the excess root crop was wasted. As stressed earlier, of course, these adjustments of intercrop and sole crop areas imply much greater precision than the farmer can possibly command in practice. Moreover, the balancing of calories and protein as outlined assumes not only that there are no other constraints on crop proportions but also that it is only protein quantity and not quality that matters.

Despite its problems this calorie/protein analysis shows an important approach that might be extended to many other studies where an intercrop has to be evaluated for two different requirements simultaneously. A further, and perhaps simpler, example is where different parts of the crops are used for different purposes. A situation where each crop produces both grain (for human consumption) and animal fodder is illustrated in Fig. 4b. For a requirement of 2 t of grain and 4 t of fodder the minimum area of sole crops is 1.56 ha (1.12 ha A and 0.44 ha B), while an intercrop of 1.30 LER (La = 0.55, Lb = 0.75) requires only 1.44 ha, a saving of 8% of the land area. This area of intercrop exactly fulfils the protein requirement but produces 48% extra grain. In theory an ELER type of calculation can again be done, showing that by growing partly the intercrop and partly sole A the exact requirements can be met on only 1.38 ha. But again this implies a very precise adjustment, and one which in fact provides little further saving in total land area. For this particular example, therefore, the preferred system would probably be to grow only the intercrop. Compared with sole cropping, the advantage of the intercrop would probably be seen as producing the minimum requirements of both protein and calories on slightly less area, and at the same time producing considerable extra grain that might perhaps be stored or sold. In effect, this approach would be analogous to that of broad limits outlined earlier, the aim being to ensure minimum requirements rather than effect some precise balance of the two crops.

CONCLUSIONS

Calculation of the basic biological efficiency of a given intercropping system is almost always worthwhile in any evaluation process. For many situations (e.g. physiological studies) it may be an end in itself. But even for more practical situations it is still useful because it indicates the maximum level of advantages that can be attained in any subsequent analyses. Biological efficiency is conveniently measured using relative units, but it is re-emphasized that there is much greater scope for using absolute yields than seems to be currently realized.

The use of 'practical' units such as money or food values does not in itself constitute a practical analysis unless there is some recognition of the fact that there may be constraints on the amounts or proportions of the different crops the farmer needs to grow. However, taking these practical requirements into account raises considerable problems when evaluating an intercropping system that does not exactly meet these requirements. The common approach has been to assume that the farmer can adjust the amounts or proportions of crops by growing an appropriate ratio of the intercrop and one of the sole crops. A major problem with this approach seems to be that the analyses assume much greater precision of adjustment than can possibly be commanded by the farmer. It is thus proposed that it might be more realistic to consider practical requirements in terms of broader limits where, for example, an intercropping system may have to be within certain limits of crop ratios, or where it may have to meet certain minimum yield requirements. A further advantage of this approach is that it can easily be applied to the much neglected situation where for a practical analysis the two crops should be evaluated differently (e.g. one as a food crop and one as a cash crop).

The analysis outlined for evaluating two different products from each crop simultaneously (e.g. calories and protein, or grain and fodder) would seem to merit further consideration. Although adjustments can be made with sole crop areas to meet very exact requirements these again may be too precise to represent a practical analysis; again a concept of at least ensuring some minimum level of production for each product might be more appropriate.

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