



Evaluating Biological Productivity in Intercropping Systems with Production Possibility Curves

Radha Ranganathan, Marcel Fafchamps* & Thomas S. Walker

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT),
Pantancheru, Andhra Pradesh 502 324, India

(Received 1 March 1990; accepted 29 October 1990)

ABSTRACT

Drawing on the notion of production possibility curves from economics literature, an analytical procedure for evaluating trade-offs in biological productivity in intercropping experiments is presented. Yield trade-offs between species are evaluated by plotting the normalised yields of the two competing crops on a graph. The resulting shape of the curve passing through the scatter of mean treatment-yield observations indicates the nature of the relationship between the crops: complementary, if the curve is convex; competitive, if concave, and independent or one where the competitive ability of both species is the same, if the estimated relationship is a straight line between the sole crop yields. A 'global' index of biological productivity is defined as the ratio of the area under the curve to the area under the straight line joining the sole crop yields. The procedure for the index's computation is described, the index estimated over a range of intercropping situations, and its implications for experimental research and extension are discussed. The proposed index is similar to the Land Equivalent Ratio (LER) in its interpretation but overcomes some of the weaknesses of the LER.

INTRODUCTION

Biological productivity in intercropping systems is most often summarised by Land Equivalent Ratios (LERs), which represent how much (more or less)

* Present address: Food Research Institute, Stanford University, Stanford, California 94305, USA.

land would be necessary to achieve the same joint output if the crops were grown separately (Willey, 1979). The popularity of LERs springs from several advantages over competing productivity measures (Ofori & Stern, 1987). LERs are easy to compute and they are flexible. Modifications appropriate to specific contexts, such as varying species duration in multiple cropping in irrigated agriculture (Hiebsch, 1978) can readily be incorporated.

Although LERs have several attractive features, they may convey an incomplete picture of relative performance between intercrops and sole crops. This paper is motivated by two weaknesses of LERs. First, LERs are localised measures of biological productivity. As such, they are inefficient in summarising and communicating all the information on yield in intercropping experiments (Vandermeer, 1989). Although researchers, such as Willey & Osiru (1972) and Mead & Willey (1980), take great care to point out what should go into the numerator and denominator of LERs, calculated and presented LERs ultimately depend on experimental objectives whose interpretation is at the discretion of the researcher (Francis, 1989).

Secondly, LERs do not easily lend themselves to economic interpretation. Economics has not contributed much to the evaluation of productivity in intercropping experiments as evaluation in economic terms is often thought to be inappropriate (Ofori & Stern, 1987). Attempts, such as Mead & Willey's (1980), to come to grips with a multiplicity of LERs by incorporating information on supposed farmer behaviour do not rest on solid economic foundations nor have they been supported empirically.

In this paper, we present a summary index of biological productivity in intercropping experiments, describe the procedures for its computation, estimate the index over a range of intercropping situations, and discuss its implications for experimental research. The measure borrows on the notion of production possibility or product transformation curves which have been applied to illustrate economic principles ranging from the theory of the firm (Henderson & Quandt, 1971) to the theory of comparative advantage (McCloskey, 1985).

The use of production possibility curves to describe complementarity or competitiveness between enterprises on farms is not new in agricultural research. For example, production possibility curves have been used by Filius (1982) and Tisdell (1985) as a theoretical device to illustrate complementarity or competition between agricultural and forestry systems. The spirit of production possibility curves also underlies a graphical approach, elaborated by Pearce & Gilliver (1979), to evaluate trade-offs in intercropping treatments. But such curves are not estimated *per se*, and their mathematical procedures are developed independently of microeconomic

principles. To the authors' knowledge, however, the concept of production possibility curves has never been applied to estimate biological productivity from experimental data on production alone.

Our estimated index uses all the yield information in an intercropping experiment; hence, it is a 'global' and not a 'local' measure which is more narrowly based on a subset of yield information from selected treatments. Moreover, the framework on which it is founded gives firm guidelines on the relative economic potential of intercropping *vis-à-vis* sole cropping. These two attributes of the proposed index come at the cost of computational complexity. Therefore, our proposed method of evaluating biological productivity complements and does not replace LERs.

CONTEXT AND CONCEPTS

The method proposed in this paper is designed to answer questions relating to relative biological productivity between intercropping and sole cropping alternatives for different species combinations. The emphasis is on field-level yield interactions under appropriate crop management. That focus is consistent with much of the intercropping literature: the sole crop treatments whose yields figure in the denominator of LER calculations should be planted at optimal densities (Huxley & Maingu, 1978).

The relevant questions address both research and extension issues. For which cropping systems is investment in intercropping research justified? (Such investment could take the form of cultivar screening or even breeding in intercropping conditions.) Which cropping systems should be extended to farmers as intercrops? Which should be transferred as sole crops?

These questions centre around larger, more general issues of relative biological productivity. Specific recommendations on densities or row arrangements are not at issue. Such recommendations depend on location-specific soil, climatic, and economic conditions. Such specific questions are often best answered by farmers through trial and error in adjusting information to their local circumstances and changing prices (Walker & Ryan, 1990).

General questions apply with greater relevance to some economies than to others. The indexing of relative biological productivity in yield is more relevant for land-scarce economies than for land-abundant societies.

The understanding of relative biological productivity under optimal crop management also attains greater importance as farmer circumstances approach experimental station conditions. In many developing countries, farmer circumstances depart significantly from experimental station conditions (Lightfoot & Tayler, 1987). Also, relative biological productivity

may figure as only one of several explanations for farmers' decisions to mix crops in preference to planting in pure stands (Norman, 1974). Therefore, one could still make a case for investing in intercropping research and extension irrespective of the findings on relative yield differences between sole and intercrop alternatives grown under optimal crop management in experimental stations. Nonetheless, experimental station results with optimal crop management for given end use objectives provide a valuable benchmark for the best ways to grow crops.

A Yield Advantage Index

The intuition behind the method proposed here is simple: trade-offs in biological productivity between species in intercropping experiments are evaluated by plotting the results of an intercropping experiment on a graph with the yield of one crop on one axis and the yield of the second on the other. A scatter of points is obtained, each point corresponding to a mean treatment yield in the experiment. Some of these points are on the axes—the sole crop yields—while others lie between the axes—the intercrop yields. Points on the straight line joining the sole crop yields are those treatments for which LERs equal 1, i.e. one could get just as much output by growing the crops separately as together. For points lying above the line, the LERs are greater than 1, indicating that intercropping is biologically more productive than sole cropping, the converse holds for points lying below the line.

A line or a curve is fitted to the scatter of points. If the line is convex (case A in Fig. 1), the two crops interact positively. If it is concave (case C in Fig. 1), the two crops are competitive. A straight line (case B in Fig. 1) between the sole crop yields indicates an equal competitive ability.

A measure of biological productivity is obtained by taking the ratio of the area under the curve to the area under the straight line: if the curve is concave, the ratio will be smaller than 1, indicating competition; if it is convex, the ratio will be greater than 1 showing complementarity. The ratio defines the Yield Advantage Index (YAI), a quantity similar in its interpretation to an LER but with global instead of localised significance.

Production possibility curves

Graphs with outputs on the axes and curves representing joint production have been used as an heuristic device by economists since the last century. Such relationships are called production possibility curves showing the combinations of maximum output obtained from a given amount of resources.

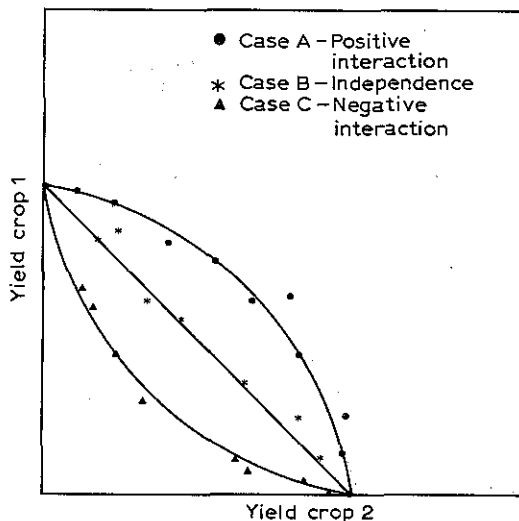


Fig. 1. Three cases of yield interactions between species in intercropping experiments.

When economists refer to production possibility curves, complementary, supplementary, and competitive relationships are defined mathematically and are illustrated in Fig. 2. Segment AB denotes complementarity because more of crop 2 can be produced as the output of crop 1 rises. A small region of supplementarity occurs near B where production of crop 2 remains constant as the output of crop 1 rises. Segment BC indicates competition

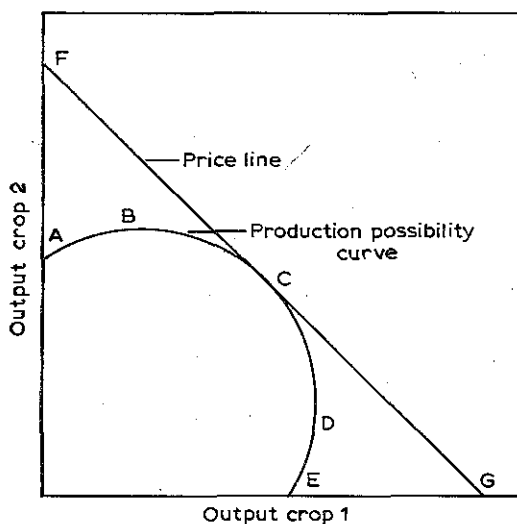


Fig. 2. Economic interpretation of production possibility curves.

because (over that range) a rise in the output of crop 1 is accompanied by a fall in the production of crop 2.

In intercropping experiments, cases of economic complementarity are unlikely to arise because the intercropped yield of one species seldom exceeds the sole crop yield of the same species. Similarly, case C in Fig. 1 receives scant attention in the economics literature, because it shows increasing returns to specialisation in production. In contrast, in experimental studies of intercropping, case C could be quite common when crops are characterised by severe competition for resources.

The main attraction of production possibility curves is the ease of economic interpretation. Assuming farmers prefer more to less, the optimal point of production corresponds to the tangency of a price line (FG) to the production possibility curve. A price line reflects a fixed value of production, i.e. the total value of the crops expressed as the sum of their constituent values. The line gives a locus of points of the same value of production for fixed prices and variable quantities of products. For example, in Fig. 2, the value of production at F, C, and G are all the same. The line is called a price line because its slope is the negative of the ratio of the output prices. For price line FG, indicating the hypothetical case of the same price for both crops, economic optimality is achieved at point C because no other point on production possibility curve AE will give a higher value of production for those fixed output prices. Increasing the price of crop 1 results in a steeper price line as economic optimality shifts towards D. Conversely, raising the price of crop 2 gives a flatter price line, and optimal production moves closer to B.

For the case A scenario of a positive interaction between intercrops in Fig. 1, a wide range of relative prices would give the result that intercropping was economically optimal. For case C of negative interactions, no rational farmer would choose an intercropping system because more value of production could always be obtained by planting either crop 1 or crop 2 than by growing both.

For our purposes, the point of economic optimality is of minor significance. The shape of the production possibility curve indicating the range over which sole cropping or intercropping is dominant is of major importance.

How far does joint production of intercrops on experimental stations deviate from the economist's conceptual mapping of a fixed amount of land, labour, and capital resources into production possibilities at the firm or farm level? One source of deviation warrants comment. Measuring biological productivity in yield is equivalent to holding land constant, but labour and capital resources do vary from treatment to treatment. On experimental stations, labour is usually applied until its marginal productivity approaches

zero; thus, differences in labour use between treatments are not a major source of concern in evaluating biological productivity from the land-based perspective of yield. Large disparities in capital intensity among treatments do, however, invalidate the economic tenets underlying production possibility curves. For that reason, yield data from treatments grown under highly protected and/or fertilised, cash-intensive conditions should not be combined with data from treatments cultivated in an unprotected and low fertility environment even within the same site. Separate production possibility curves should be estimated for the two different types of environments to determine changes in the curvature of yield interactions. In the concluding section, we comment on extensions to this approach when data are available on input use and when treatments vary substantially in their capital expenditure.

METHODS

The CES/CET functional form

To estimate statistically the curve that best fits a scatter of points, it is necessary to first assume that the curve takes a certain mathematical form. This form should be flexible enough to capture the range of crop enterprise interactions described in Fig. 1 but also compact enough to summarise the relationship in as few parameters as possible.

Several functional forms were tried. The one that best satisfied the flexibility and compactness conditions was the Constant Elasticity of Substitution/Constant Elasticity of Transformation (CES/CET) functional form (Arrow *et al.*, 1961).

The equation of the CES/CET is:

$$b = [aY_1^c + (1-a)Y_2^c]^{(1/c)} \quad (1)$$

where Y_1 and Y_2 are yields of the component crops and a , b and c are parameters to be estimated. When c is 1, the equation is that of a straight line; if it is greater than 1 the curve is concave; if it is less than 1 the curve is convex. Thus one parameter, c , in the CES/CET functional form directly provides information on the nature of species interactions. The other two parameters position the curve: increasing b pushes the curve from the origin, while modifying a rotates the curve towards one axis.

Although the CES/CET is compact, it is not flexible enough to cover the range of interactions shown in Fig. 2. In particular, all points on the CES/CET curve are restricted to lie on or below the sole cropping yields. In other words, it cannot portray the case of economic complementarity

depicted by segment **AB** of Fig. 2, where an increase in the yield of one crop is accompanied by a heavier yield of the other. But this restrictive property of the CES/CET can be a virtue: economic complementarity cannot be artificially generated by some peculiarity of the data. In rare cases where economic complementarity is suggested by prior information and supported by a graphical analysis, the CES/CET functional form should be discarded.

Because the CES/CET in eqn (1) is non-linear in parameters, a non-linear, least-squares regression algorithm (SHAZAM) was used to estimate a , b and c such that the sum of squared residuals was minimised. The use of non-linear least squares analysis requires some interaction between the user and the algorithm (Kmenta, 1971). For our problem, the main steps and/or considerations included the following:

- (i) Equation (1) was rewritten and simplified to:

$$1 = b^* + aY_1^c + (1 - a)Y_2^c \quad (2)$$

where $b^* = 1 - b^c$.

- (ii) Mean treatment crop yields were normalised by dividing by the grand mean of the intercropped and sole cropped yields.
- (iii) All zero yield values were recoded as very small positive numbers, e.g. 0.001.
- (iv) A starting value of 0.5 was assigned to a and 0.1 to b^* . The starting value for c depended on the likely shape of the curve suggested by the scatter diagram. For the case of positive yield interactions (case A in Fig. 1), a starting value of 1.5 was appropriate; for negative interactions (case C in Fig. 1), a starting value of 0.6 gave satisfactory results.

The above considerations were necessary to facilitate the estimation of the parameters with the non-linear least squares algorithm. One of the main motivations for rewriting eqn (1) was to ensure that division by zero did not take place in the algorithm. The data were normalised for ease of calculation.

Finally, similar to LER calculations, the results are sensitive to the magnitude of the sole crop yields. The sole cropping values anchor the curve to the axes and determine its shape, i.e. the nature of the relationship between the crops. Intercropping experiments are often designed with a single or few sole crop treatments, apparently reflecting researchers' beliefs that optimal densities and management practices are better known for sole stands than for intercrops. Because the estimation method is based on the minimisation of the sum of squared residuals, such a small number of sole crop observations is insufficient to ensure that the fitted curve crosses the axes near the sole crop yields. To anchor the curve to the axes at the vicinity of the

sole crop yields it is necessary to increase the number of observations for sole crop yields. We found that in experiments with only one sole crop treatment, the average yield had to be repeated four to six times to anchor the curve through or close to the sole crop yield. This procedure is tantamount to weighted least squares and is equivalent to saying that researchers know considerably more about the biological productivity of sole crops than of component intercropping systems.

Going from the estimated production possibility curve to our proposed measure of biological productivity requires the integration of the estimated curve. Analytical integration of the CES/CET is difficult, if not impossible. Numerical integration is, however, quite straightforward and can be done easily on any computer. Fortunately for the CES/CET, the curvature parameter c , bears a direct and unambiguous relationship with the YAI (see Appendix, Table 1). Values of 0.0, 1.0, and positive infinity for c correspond to 0.0, 1.0, and 2.0 for the YAI.

The data

Data were obtained from rain-fed intercropping experiments at ICRISAT Center, Patancheru, India. The experiments were selected to determine how well the CES/CET functional form stood up to the range of experience of potential intercropping interactions conveyed in Fig. 1.

Data set 1

This data set was obtained from an experiment over three cropping years (1978–1979, 1979–1980, and 1980–1981) on Vertisols (Rao & Willey, 1983). Intercrops of pigeonpea (*Cajanus cajan* (L.) Millsp.) and sorghum (*Sorghum bicolor* (L.) Moench) were grown with the following row arrangements:

- 1 sorghum:1 pigeonpea:1 sorghum with 45 cm between rows
- 1 pigeonpea:2 sorghum:1 pigeonpea with 30 cm between rows
- 1 sorghum:2 pigeonpea:1 sorghum with 30 cm between rows

The treatments were laid out as main plots and were split for five pigeonpea plant populations (1.5, 4, 7, 10 and 13 plants/m²). The one sole sorghum treatment was planted at a density of 16.7 plants/m². There were four replicates each year.

The five sole crop yields for pigeonpea averaged over replicates ranged from 1.4 to 1.5 t/ha; the average sorghum yield was 4.9 t/ha. The intercropping treatment yields ranged from 0.9 and 1.2 t/ha for pigeonpea and 3.8 and 4.6 t/ha for sorghum. The treatment yield data were averaged over the three years to estimate a production possibility curve.

Data set 2

A two-year (1980–1981 and 1981–1982) experiment to study the effect of population and row arrangement in millet (*Pennisetum americanum* (L.) Leeke) and groundnut (*Arachis hypogaea* L.) intercropping was established on Alfisols (Willey *et al.*, 1987). Four millet populations (2.8, 5.6, 11.1, 22.2 plants/m²) and three row arrangements (1 millet:1 groundnut, 1 millet:3 groundnut, 1 millet:5 groundnut), with three replicates were laid out in randomised blocks. The one sole groundnut treatment was planted at a population of 33.3 plants/m².

Average sole crop groundnut yield was 1.5 t/ha while the average sole millet yields varied between 3.1 and 3.8 t/ha. Intercropped groundnut yields averaged between 0.4 and 1.3 t/ha while average millet yields in the intercrop ranged between 0.9 and 2.9 t/ha. The treatment yield data were averaged over the two years to estimate a production possibility curve.

Data set 3

These data were obtained from a mixed cropping system of *Leucaena leucocephala* (Lam), sorghum and pigeonpea to evaluate the scope for improving the productivity of sorghum/pigeonpea intercrop by introducing into the system a perennial, *Leucaena*, and to examine the usefulness of a two-way parallel-row systematic design for determining the population/spacing requirements of *Leucaena* in intercropping with annual crops. Spacing between paired rows of *Leucaena* (planted 60 cm apart) was increased systematically by 0.9 m starting from 1.35 m at one end to 4.95 m at the other end of a block. Sorghum and pigeonpea were planted in alternate rows between paired rows of *Leucaena* 45 cm apart.

Thus the proportion of *Leucaena* decreases and that of the arable crop increases horizontally. For any given *Leucaena* spacing, the distance between *Leucaena* and the annual crops is increased by dropping two rows of the latter (one on each side) vertically for every 8 m row until a sole plot of *Leucaena* is obtained at that spacing. There are thus five sole paired-row plots of *Leucaena*. One plot each of sole sorghum, pigeonpea and their intercrop was also planted. There were four replicates (ICRISAT, 1986).

Sorghum and pigeonpea yields were added and averaged over the replicates and thus treated as a single crop. Average summed sorghum/pigeonpea yields in the alleys ranged between 0.9 and 2.8 t/ha in 1984–1985, 0.2 and 1.8 t/ha in 1985–1986 and 0.03 and 1.6 t/ha in 1986–1987. Average 'sole' intercrop (i.e. intercrop of sorghum and pigeonpea) grain yields were 3.1, 2.7 and 3.3 t/ha in 1984–1985, 1985–1986 and 1986–1987, respectively. *Leucaena* was harvested 2–5 times a year when its canopy was thought to be affecting the growth of the crops. *Leucaena* in the alleys yielded on average 0.08 to 0.5 t/ha of dry matter in 1984–1985, 2.9 to 8.6 t/ha in 1985–1986 and

3.8 to 8.4 t/ha in 1986–1987. Mean sole *Leucaena* yields ranged from 0.6 to 1.2 t/ha in the first year, 8.7 to 11.2 t/ha in the second year, and 7.4 to 13.5 t/ha in third year. Production possibility curves were fitted to each year's yield data to determine differential age effects of *Leucaena* on the annual crops.

DISCUSSION

The fitted production possibility curves are presented with the normalised mean treatment yield data in Figs 3, 4 and 5; estimated coefficients are presented in Table 1. For the three data sets, the fit is satisfactory, and the estimated shape of the curve corresponds well with prior agronomic knowledge about the relationship between the crops. The sorghum/pigeonpea intercrop, for instance, is known to display strong temporal complementarity. Sorghum is harvested after about 95–100 days at the end of the rainy season; pigeonpea continues growing for 80–100 days on stored soil moisture (Rao & Willey, 1983). The strong positive yield interactions between a fast growing, early maturing crop and a late maturing one is vividly portrayed by the curve in Fig. 3.

In contrast, the yield advantage of the millet/groundnut intercrop compared to sole cropping is attributed to greater efficiency of resource use (Willey *et al.*, 1987). But the size of the intercropping advantage is small compared with the relative yield performance of the sorghum/pigeonpea

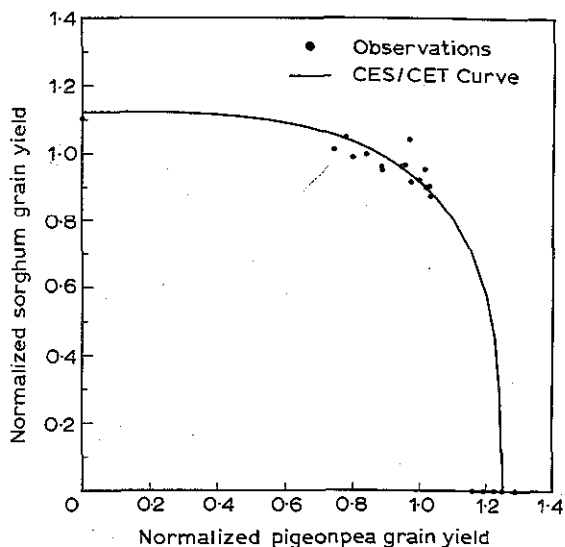


Fig. 3. Estimated production possibility curve of the sorghum/pigeonpea experiment.

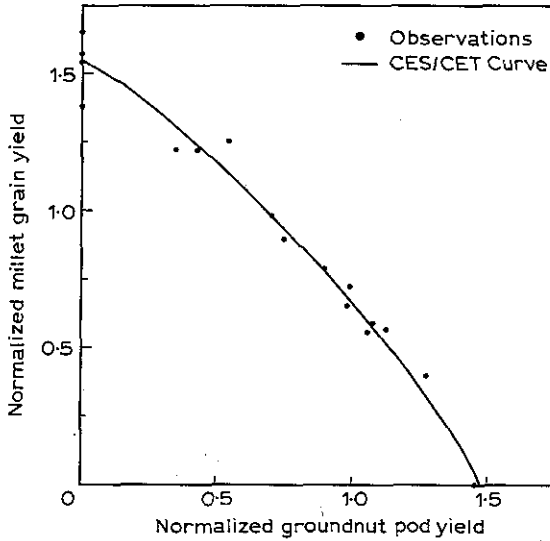


Fig. 4. Estimated production possibility curve for the groundnut/millet experiment.

intercrop. The yield relationship in Fig. 4 is best described as independence of millet and groundnut.

For the agroforestry data set, the relationship as indicated by the curves in Fig. 5 is marked by competition. *Leucaena* roots were found near the soil surface competing with the annual crops for soil moisture (ICRISAT, 1986). Pigeonpea was highly susceptible to competition from the *Leucaena*.

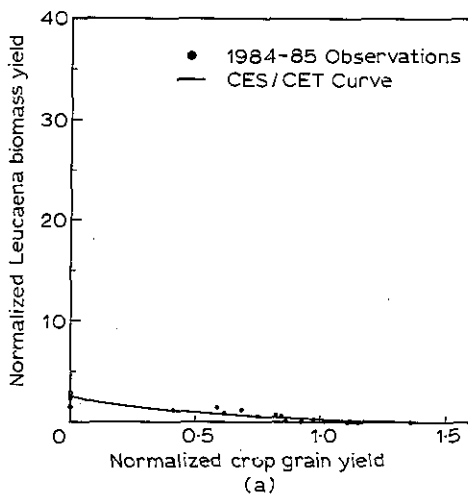


Fig. 5. Estimated production possibility curve for the *Leucaena*/sorghum/pigeonpea agroforestry trial by year.

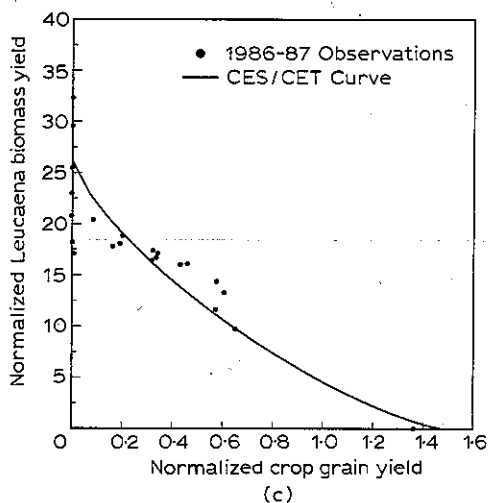
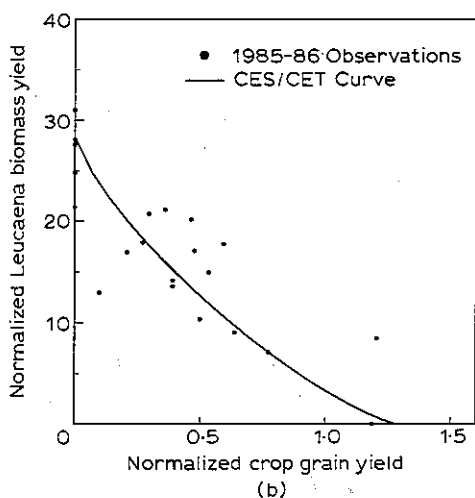


Fig. 5—contd

The size and direction of intercrop yield interactions estimated with the CES/CET production possibility curves in Figs 3–5 are reflected in values of the YAI of 1.79 for the sorghum/pigeonpea intercrop, 1.16 for the millet/groundnut intercrop, and 0.64, 0.76 and 0.73 for the *Leucaena*/sorghum/pigeonpea intercrop in 1984, 1985 and 1986, respectively (see Table 1).

Turning to the economic interpretation of the three data sets, for almost all price ratios of pigeonpea to sorghum, farmers would choose an intercrop over sole crops of either species. The estimated curve in Fig. 3 is consistent with the recommendation to invest agricultural research and extension

TABLE 1
Estimated Parameters of the CES/CET Function and the Yield Advantage Index (YAI)

System	Estimated parameters ^a			
	b* (SE)	a (SE)	c (SE)	YAI
Sorghum/ pigeonpea	-0.15 (0.02)	0.59 (0.023)	3.28 (0.281)	1.79
Millet/ groundnut	-0.19 (0.01)	0.52 (0.008)	1.18 (0.05)	1.16
<i>Leucaena</i> / sorghum/pigeonpea				
1984-1985	-0.26 (0.02)	0.61 (0.02)	0.70 (0.07)	0.64
1985-1986	-0.24 (0.02)	0.46 (0.023)	0.79 (0.079)	0.76
1986-1987	-0.24 (0.015)	0.41 (0.019)	0.76 (0.058)	0.73

^a The equation used in estimating the parameters is: $1 = b^* + aY_1^c + (1 - a)Y_2^c$, where $b^* = 1 - b^c$.

resources in the sorghum/pigeonpea intercrop which is characterised by superior relative yield performance. Such investment could take the form of cultivar screening in intercropping conditions or of demonstrations assigning priority to the sorghum/pigeonpea intercrop *vis-à-vis* sole crops of sorghum or pigeonpea.

On the basis of biological productivity, the case for the millet/groundnut intercrop is much weaker. The small intercropping yield advantage appears not to warrant favouring millet/groundnut over sole cropping alternatives in decisions on research and extension resource allocation. The choice of sole cropping or intercropping depends largely on the price ratio of groundnut to millet in Fig. 4. Positive yield interactions are not large enough to offset the importance of economic considerations in the choice of cropping systems. Highly negative yield interactions swamp economic considerations in each year of the agroforestry trial. For all output prices, hedgerow intercropping with *Leucaena* is economically inferior to producing *Leucaena* in sole stands.

These results, based on experimental data, are consistent with farmers' intercropping practices in India's Semi-Arid Tropics. The hybrid sorghum/pigeonpea intercrop enjoys rising popularity among SAT farmers (Walker & Ryan, 1990). Initially, the sorghum hybrids were demonstrated in sole stands. More recently, the hybrid sorghum/pigeonpea intercrop is more

TABLE 2
LERs for the Sorghum(S)/Pigeonpea(P) Intercropping Experiment

Row arrangement	Pigeonpea population (plants/m ²)					
	1.5	4	7	10	13	Mean
2S-1P	1.57	1.58	1.63	1.58	1.58	1.59
2S-2P	1.51	1.72	1.65	1.61	1.64	1.63
2P-2P	1.54	1.63	1.65	1.61	1.62	1.61
Mean	1.56	1.64	1.64	1.60	1.62	1.61

frequently observed in farmers' fields. In contrast, observations of the millet/groundnut intercrop outside experimental stations are rare. Likewise, *Leucaena* is mainly planted on field boundaries and is seldom interspersed with field crops in India's Semi-Arid Tropics.

How do the values of the YAI compare with the estimated treatment LERs? The estimated LERs for the sorghum/pigeonpea intercropping experiment in Table 2 and for the millet/groundnut intercropping experiment in Table 3 are the same order of magnitude as the values reported for the YAI. For these two multi-year data sets, our proposed method did not contribute much additional information over tabulated LERs. The treatment LERs were tightly clustered around their grand mean LER for both experiments.

When the estimated variance in LERs across treatments is greater, the two summary measures of relative productivity can give conflicting results. For example, the estimated LERs in the *Leucaena* alley cropping experiment show more variability between 1985-1986 and 1986-1987 than comparable values for the YAI. (LERs for 1984-1985 were not calculated as the 'sole' plots of sorghum/pigeonpea were not free from the influence of

TABLE 3
LERs for the Millet(M)/Groundnut(G) Intercropping Experiment

Millet population (plants/m ²)	Row arrangement			
	MG	MGGG	MGGGGG	Mean
2.8	1.12	1.13	1.14	1.13
5.6	1.19	1.15	1.09	1.14
11.1	1.09	1.13	1.15	1.12
22.2	1.04	1.10	1.10	1.08
Mean	1.11	1.13	1.12	1.12

Leucaena. In subsequent years, polythene barriers were placed around these plots to minimise the influence of *Leucaena*.) The alleys at a wider spacing of 4.05 and 4.95 m gave LERs centred on 1.0 in 1985–86 (Table 4). In 1986–87, estimated LERs for 4.05 and 4.95 m spacings were substantially less than 1.0. In contrast, the curvature of the estimated production possibility relationships in Fig. 5 for 1985–86 and 1986–87 are about the same for the two cropping years; hence, the estimated values for c and for the YAI are not appreciably different. For each year, they tell the same story: marked competition. In the middle panel of Fig. 5 for 1985–1986, the outliers above the curve are all from the wider spacing of 4.05 or 4.95 m; they do not weigh enough in the regression analysis to alter the estimated strongly competitive relationship.

The estimated LERs are also more sensitive to the basis for sole crop evaluation than the estimated YAI. In the *Leucaena* hedgerow intercropping experiment, LERs can be based on the 'sole' sorghum/pigeonpea intercrop yields (Table 4), or on the one sole sorghum and sole pigeonpea treatment included in the experiment (Table 5). In 1985–1986, largely because of drought, the mean yield of the sole pigeonpea treatment across the four

TABLE 4
LERs Based on the 'Sole' Sorghum/Pigeonpea Intercrop Yields,^a for the
Leucaena/Sorghum/Pigeonpea Agroforestry Experiment

No. of alternate rows of sorghum/pigeonpea	Spacing between <i>Leucaena</i> alleys (m)				
	1.35	2.25	3.15	4.05	4.95
1985–1986					
1 row	0.55	0.79	0.88	1.07	1.00
2 rows		0.82	0.84	1.02	1.12
3 rows			0.79	0.99	1.14
4 rows				0.86	0.82
5 rows					0.91
1986–1987					
1 row	0.53	0.68	0.68	0.72	0.67
2 rows		0.67	0.72	0.74	0.77
3 rows			0.85	0.80	0.82
4 rows				0.85	0.77
5 rows					0.76

^a The experiment was laid out in a two-way systematic design. Spacing between paired rows of *Leucaena* was increased starting from 1.35 m at one end to 4.95 m at the other end of the block. Alternate rows of sorghum and pigeonpea were planted between the paired rows of *Leucaena*. Sole crops of sorghum, pigeonpea and their intercrop were planted.

TABLE 5

LERs, Based on Sole Sorghum and Sole Pigeonpea Yields, for the *Leucaena*/Sorghum/
Pigeonpea Agroforestry Experiment in 1985-86^a

No. of alternate rows of sorghum/pigeonpea	Spacing between <i>Leucaena</i> alleys (m)				
	1.35	2.25	3.15	4.05	4.95
1 row	0.59	0.82	1.08	1.34	1.32
2 rows		0.49	0.94	1.45	0.99
3 rows			0.96	1.19	1.64
4 rows				1.21	1.47
5 rows					1.36

^a The experiment was laid out in a two-way systematic design. Spacing between paired rows of *Leucaena* was increased starting from 1.35 m at one end to 4.95 m at the other end of the block. Alternate rows of sorghum and pigeonpea were planted between the paired rows of *Leucaena*. Sole crops of sorghum, pigeonpea and their intercrop were planted.

replicates was only 0.17 t/ha, resulting in the inflated LERs in Table 5. At the closer spacings of 1.35, 2.25 and 3.15 m, pigeonpea yields in the *Leucaena* alleys were negligible; therefore, the abnormally low pigeonpea sole crop yields did not have a telling effect on estimated LERs. But at the wider spacings of 4.05 and 4.95 m, the effect was pronounced. The mean LER of the nine treatments at the two wider spacings was 0.99 in Table 4 compared to 1.33 in Table 5.

Changing the basis for the sole crop yield evaluation did not noticeably affect the results from the production possibility curve analysis. Re-estimating the production possibility curve in Fig. 5(b) based on the sole pigeonpea and sole sorghum yields instead of on the 'sole' sorghum/pigeonpea intercrop yields gave similar estimates to those reported in Table 1 for 1985-1986. The re-estimated curve resulted in the same value (0.76) for the YAI.

CONCLUSIONS

In this paper, a global measure of biological productivity in intercropping has been presented. The proposed YAI provides a more efficient way of summarising yield data on relative productivity performance in intercropping experiments than LERs which are localised measures of yield advantage in intercropping. Computation of the YAI is considerably more tedious than the calculation of an LER, but once the solution algorithm is set up, the method takes little time. Where a non-linear least squares algorithm is not

available to estimate CES/CET production possibility curves, scatter diagrams of normalised mean treatment yields are still a useful diagnostic tool to provide insight on the outline of a production possibility surface and on outliers from a visualised frontier. Such information should be complementary to that conveyed in LER tables and should assist in identifying tendencies or outliers that require explanation of underlying processes.

The fitting of production possibility curves to experimental data can be improved through better experimental design. Intercropping treatments should be selected to provide coverage over the (yield, yield) coordinate space. For example, in the sorghum/pigeonpea experiment, inclusion of a treatment of four rows of sorghum to one row of pigeonpea or four rows of pigeonpea to one row of sorghum could have resulted in better coverage of the (yield, yield) space in Fig. 3 and in more reliable estimates.

An emphasis on biological productivity under optimal management and the problems encountered in anchoring the curves to the axes in the estimation process again highlight the importance of defining sole crop yields accurately. Sole crops should be planted on time with a 'best bet' or recommended population density, row width, and improved cultivar. Agronomists should have a good idea of what these recommendations are. If such information is not available, i.e. if agronomists do not know how to produce the sole treatment in a technically efficient manner for the planned 'normal' year, then an evaluation of relative biological productivity does not make much sense.

Both sole and intercropped treatments should be managed optimally, but optimal management does not imply identical management practices. Imposing management practices, designed to minimise interspecies competition in the intercrop, on the sole crop treatments defeats the purpose of productivity evaluation (Walker, 1987). In the agroforestry trial, the estimated YAI likely overstates the relative performance of alley cropping because the sole stands of *Leucaena* were not managed optimally (Ong, in press). A different pruning strategy and planting density could have significantly increased the yield of sole *Leucaena*.

The role of the environment in affecting the shape and location of the curves is more problematic. We have drawn on multi-year data sets and assumed that the experimental years represent the 'average' weather. Alternatively, one could estimate a curve for each year and carry out F tests to determine whether or not the data could be pooled. Visual inspection of the annual sorghum/pigeonpea and millet/groundnut data suggested that year effects were not large enough to warrant separate estimation. Like competing evaluation criteria, the use of a relative productivity measure, derived from possibility curves, does not diminish the need for intuition in

reporting the temporal context of the results nor does it substitute for simulation models of intercrops.

Finally, the concept of a production possibility frontier can be generalised in several ways. For example, it can be combined with the production function approach familiar to economists or with some models used by production ecologists and crop physiologists. If information was available on input use then the left hand side of eqn (1) can be replaced by a production function capturing the impact that inputs have on joint output (Hexem & Heady, 1978). The production possibility frontier can also be derived under more general conditions using models of intra- and inter-specific competition (Spitters, 1983).

ACKNOWLEDGMENTS

The authors thank Drs J. L. Monteith, C. K. Ong, F. R. Bidinger, C. S. Gold, D. Neeley and M. Anders for their comments. Approved as ICRISAT JA no. 882.

REFERENCES

- Arrow, K. J., Chenery, H. B., Minhas, B. S. & Solow, R. M. (1961). Capital-labor substitution and economic efficiency. *The Review of Economics and Statistics*, August, 225-50.
- Filius, A. M. (1982). Economic aspects of agroforestry. *Agroforestry Systems*, 1, 29-39.
- Francis, C. A. (1989). Biological efficiencies in multiple-cropping systems. *Advances in Agronomy*, 42, 1-36.
- Henderson, J. M. & Quandt, R. E. (1971). *Microeconomic Theory*. McGraw-Hill, New York, USA.
- Hexem, R. W. & Heady, E. D. (1978). *Water Production Functions for Irrigated Agriculture*. The Iowa State University Press, Ames, Iowa.
- Hiebsch, C. (1978). Comparing intercrops with monoculture in agronomic, economic research on soils of the Tropics. *Annual Report 1976-77*. North Carolina State University, Soil Science Department, Raleigh.
- Huxley, P. A. & Maingu, Z. (1978). Use of a systematic spacing design as an aid to the study of intercropping: some general considerations. *Experimental Agriculture*, 14, 49-56.
- ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) (1986). *Annual Report 1985*. ICRISAT, Patancheru PO, A.P. 502 324, India.
- Kmenta, J. (1971). *Elements of Econometrics*. Macmillan Company, New York.
- Lightfoot, C. W. F. & Tayler, R. S. (1987). Intercropping sorghum with cowpea in dryland farming systems in Botswana. I. Field experiments and relative advantages of intercropping. *Experimental Agriculture*, 23, 425-34.

- McCloskey, D. N. (1985). *The Applied Theory of Price*. Collier Macmillan, New York.
- Mead, R. & Willey, R. W. (1980). The concept of a 'Land Equivalent Ratio' and advantages in yields from intercropping. *Experimental Agriculture*, **16**, 217-28.
- Norman, D. W. (1974). Rationalizing mixed cropping under indigenous conditions: the example of Northern Nigeria. *The Journal of Development Studies*, **11**(1), 3-21.
- Ofori, F. & Stern, W. R. (1987). Cereal-legume intercropping systems. *Advances in Agronomy*, **41**, 41-90.
- Ong, C. K. (in press). Interactions for light, water and nutrients in agroforestry systems. In *Applications of Biological Research in Asian Agroforestry*, ed. Martha E. Avery, M. G. R. Cannell & C. K. Ong. Oxford University Press, Delhi.
- Pearce, S. C. & Gilliver, B. (1979). Graphical assessment of intercropping methods. *Journal of Agricultural Sciences, Cambridge*, **93**, 51-8.
- Rao, M. R. & Willey, R. W. (1983). Effects of plant population and row arrangement in sorghum/pigeonpea intercropping. *Field Crop Abstracts*, **32**(1), 1-10.
- Spitters, C. J. T. (1983). An alternative approach to the analysis of mixed cropping experiments. 1. Estimation of competition effects. *Netherlands Journal of Agricultural Sciences*, **31**, 1-11.
- Tisdell, C. A. (1985). Conserving and planting trees on farms. Lessons from Australian cases. *Review of Marketing and Agricultural Economics*, **53**(3), 185-94.
- Vandermeer, J. H. (1989). *The Ecology of Intercropping*. Cambridge University Press, Cambridge.
- Walker, T. S. (1987). Economics for agroforestry interventions in India's SAT: implications for research resource allocation at ICRISAT. *Economics Group Progress Report 79*. ICRISAT, Patancheru PO, A.P. 502 324, India.
- Walker, T. S. & Ryan, J. G. (1990). *Village and Household Economics in India's Semi-Arid Tropics*. The Johns Hopkins University Press, Baltimore, USA.
- Willey, R. W. (1979). Intercropping—its importance and research needs. 1. Competition and yield advantages. *Yield Crop Abstracts*, **32**(1), 1-10.
- Willey, R. W. & Osiru, D. S. O. (1972). Studies on mixtures of maize and beans (*Phaseolus vulgaris*) with particular reference to plant population. *Journal of Agricultural Sciences*, **79**, 517-29.
- Willey, R. W., Reddy, M. S. & Natarajan, M. (1987). Conventional cropping systems for Alfisols and some implications for agroforestry systems. In *Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimising the Productivity of SAT Alfisols and Related Soils*. ICRISAT, Patancheru PO, A.P. 502 324, India.

APPENDIX

TABLE 1
Yield Advantage Index (YAI) Corresponding to Different
Values of c

c	YAI	c	YAI	c	YAI
0.00	0.00	1.00	1.00	1.95	1.55
0.10	0.02	1.05	1.05	2.00	1.57
0.15	0.025	1.10	1.09	2.10	1.60
0.20	0.03	1.15	1.14	2.20	1.62
0.25	0.05	1.20	1.18	2.30	1.65
0.30	0.08	1.25	1.21	2.40	1.67
0.35	0.13	1.30	1.25	2.50	1.69
0.40	0.19	1.35	1.28	3.00	1.76
0.45	0.26	1.40	1.31	3.50	1.81
0.50	0.34	1.45	1.34	4.00	1.85
0.55	0.41	1.50	1.37	4.50	1.87
0.60	0.49	1.55	1.39	5.00	1.89
0.65	0.57	1.60	1.42	10.00	1.95
0.70	0.64	1.65	1.44	20.00	1.97
0.75	0.71	1.70	1.46	50.00	1.98
0.80	0.77	1.75	1.48	∞	2.00
0.85	0.84	1.80	1.50		
0.90	0.89	1.85	1.52		
0.95	0.95	1.90	1.54		