ACKNOWLEDGEMENTS

Messrs. A.A. Imakuson and Y.A. Salawu are gratefully acknowledged for their skilful supervision of the experiments.

REFERENCES

Allen, D.M. and Cady, F.B., 1982. Analysing Experimental Data by Regression. Lifetime Learning Publications, Belmont, California, 394 pp.
Cashman, K., 1986. A community response to On-Farm Research; a participatory approach to sustainable food production. IITA, Ibadan, Nigeria, 57 pp.
Cochran, W.G. and Cox, G.M., 1957. Experimental Design. Wiley, New York, 593 pp.
Finlay, K.W. and Wilkinson, G.N., 1963. The analysis of adaptation in a plant-breeding programme. Aust. J. Agric. Res., 14: 742–754.
Hildebrand, P.E., 1984. Modified stability analysis of farmer-managed on-farm trials. Agron. J., 76: 271–274.
Morris, R.A., 1981. Determining fertilizer rates for crops in cropping systems. In: H.G. Zandstra, E.C. Price, J.A. Litsinger and R.A. Morris (Editors), A Methodology for On-Farm Cropping Systems Research. IRRI, Los Baños, The Philippines, pp. 104–113.
Palada, M.C. and Vogel, W.O., 1986. On-farm trials in forest-savannah transition zone. IITA, Ibadan, Nigeria, Annu. Rep. 1985: 147–162.
Smyth, A.J. and Montgomerry, R.F., 1962. Soils and Land Use in Central Western Nigeria. Government Printer, Ibadan, Nigeria, 265 pp.

Field Crops Research, 23 (1990) 279–293
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

Productivity and Risk Evaluation in Contrasting Intercropping Systems[1]

M.R. RAO[2] and M. SINGH[3]

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

(Accepted 19 October 1989)

ABSTRACT

Rao, M.R. and Singh, M., 1990. Productivity and risk evaluation in contrasting intercropping systems. *Field Crops Res.*, 23: 279–293.

Four contrasting intercropping systems, sorghum (*Sorghum bicolor* (L.) Moench)/pigeonpea (*Cajanus cajan* (L.) Millsp.), groundnut (*Arachis hypogaea* L.)/pigeonpea, sorghum/pearl millet (*Pennisetum americanum* (L.) Leeke), and groundnut/pearl millet, were evaluated along with sole crops from 1979 to 1982, each year in nine different situations spread over different soil types and agronomic managements, with the objective of analysing the productivity and risk associated with these systems. Productivity of intercrops was closely related to the diversity of the crops involved. The two pigeonpea-based systems, with an interval of about 3 months between harvests of the crops, showed a large and consistent advantage over the respective sole crops. On the basis of land productivity, sorghum/pigeonpea averaged 49% and pigeonpea/groundnut 53% advantage over their respective sole-crop yields. In economic terms, these intercrops were also more profitable than the respective sole crops. The other two systems, with only 2–4 weeks' difference between harvests of the components, showed a much lower and less-consistent advantage. The groundnut/millet recorded 18% advantage and the sorghum/millet 7% over their respective sole crops. Risk was measured by calculating the probability of success or failure of intercrops in satisfying specified quantities of yields or income in comparison with an optimal shared sole system having some of both sole crops. Pigeonpea-based intercropping systems were less risky than shared (or optimal) sole crops over a wide range of expected yields or income. There was no advantage for the sorghum/millet intercropping compared with the shared sole crops at lower expectation, and for higher expectations sole sorghum should be preferred to the intercrop. Risk from groundnut/millet was less than from the shared sole system only in limited situations. Reduced risk of pigeonpea-based intercrops was associated with higher productivity and lower variability of combined intercrop yields or income. The methods employed in this study can be extended for risk evaluation in other intercropping and mixed systems.

[1]ICRISAT Journal Article No. 878.
[2]Present address: International Council for Research in Agroforestry (ICRAF), P.O. Box 30677, Nairobi, Kenya.
[3]Present address: International Center for Agricultural Research in the Dry Areas (ICARDA), Box 5466, Aleppo, Syria.

0378-4290/90/$03.50

INTRODUCTION

Higher productivity and greater yield (or income) stability over sole crops are the main reasons why intercropping has been so important for small farmers in the tropics. Higher yields may be the result of complementary and efficient use of growth resources over time and/or space, whereas greater stability may result from reduced variability in the overall yield/returns, by way of one crop compensating for the other in the event of limited or irregular supply of growth resources. The greater the diversity of crops involved, the more likely it is that intercropping advantages are enhanced. The productivity of intercrops has generally been evaluated by considering yields, land-equivalent ratio, and monetary returns (Willey, 1979). Rao and Willey (1980) examined yield stability in intercropping and proposed some approaches to evaluate stability and risk, which formed the basis for later methodological improvements (Pearce and Edmondson, 1982; Trenbath, 1983; Mead et al., 1986).

Productivity can be judged easily from short-term evaluation of the system, but stability evaluation requires long-term observations. A few studies that evaluated the stability of intercropping have considered, in the absence of sufficient time-series data, data across sites and across years (Rao and Willey, 1980; Singh and Jha, 1984; Mead et al., 1986). Those data were not from a single experiment conducted across sites and years to reflect the location and year effects, but were drawn from different trials varying in genotypes and management. They recognized the merit of time-series data for stability evaluation, for the variability a farmer experiences over years at a given site is not the same as the variability measured over sites. This is particularly true if the sites are not appropriately clustered and production determinants such as rainfall vary greatly across sites (Evenson et al., 1978).

Though the earlier studies have shown the improved stability of some intercrops, not all of them examined the mechanism of how intercrops achieve that improved stability. Rao and Willey (1980) examined to a limited extent the compensation in sorghum/pigeonpea intercropping because of changes in soil moisture and fertility. Other variables that affect intercropping performance include weed management and plant protection, on which limited information is available. Another question is whether higher yield stability is common to all intercropping systems or specific to certain types of crop combinations.

The most useful approach suggested by Rao and Willey (1980) for risk evaluation was to calculate the probability of failure of intercrops to produce a specified income in comparison with that of the sole crops. Pearce and Edmondson (1982) suggested calculation of the joint probability of specific quantities of both crop yields, which is relevant especially to meet the subsistence needs of small farmers. Mead et al. (1986) contended that fitting an appropriate model to the data and calculation of risk from the fitted distribution is statistically more appropriate. However, the risk curves from their fitted bivariate distribution gave similar results to those obtained from the empirical risk curves. Comparison of intercrop risk against only one of the sole crops, as carried out by Mead et al. (1986), is inadequate, especially if that sole crop is not the highest-yielding one and if the farmer is interested in growing some of each of the sole crops. Hence, Rao and Willey (1980) constituted a shared-sole-crop system, where both sole crops are grown on any given land area in the same proportion as the component crop yields in intercropping. Shultz (1982) suggested that intercrops be compared against a shared sole system containing both sole crops, in a proportion that gives the least-variable returns or yields. However, neither of the approaches may result in the most profitable and productive shared sole; so there is a need to explore further what is the most appropriate sole crop for evaluating the intercropping.

This paper compares the productivity and risk of four contrasting intercropping systems, based on a study designed for the purpose and conducted with the same genotypes and known agronomic variability across sites for four years under supervision of the same persons. The data incorporated the variability caused by different weed-management and plant-protection practices. The paper also presents further refinements in methods for risk evaluation in intercropping.

MATERIALS AND METHODS

Treatments

The experiment had eight treatments, four of which were sole crops of sorghum (*Sorghum bicolor* (L.) Moench), pearl millet (*Pennisetum americanum* (L.) Leeke), pigeonpea (*Cajanus cajan* (L.) Millsp.), and groundnut (*Arachis hypogaea* L.), and the remaining four intercrops involving these: sorghum/pigeonpea; groundnut/pearl millet; groundnut/pigeonpea; and sorghum/pearl millet (Table 1). These systems differ from one another in respect of the growth pattern of the crops involved. The first two are cereal/legume combinations; the contrast between them is that while the legume (pigeonpea) in the first system grows slowly initially and matures about 3 months later than the cereal (sorghum), the legume (groundnut) in the second system matures only about 2–3 weeks after the cereal (millet) harvest. Groundnut/pigeonpea is a legume/legume combination with a temporal difference between the component crops similar to that in sorghum/pigeonpea. Sorghum/millet is a cereal/cereal combination with a temporal difference between the components similar to that of groundnut/millet (Table 1).

The trial was conducted in a randomized-block design having three replications for four years from 1979 to 1982 at ICRISAT Center, Patancheru, India. Within each year, it was located at four different sites on red soils (Alfisols) and three on black soils (Vertisols and Vertic Inceptisols). The sites

TABLE 1

Agronomic details of crops and intercropping systems

Cropping system/ Row arrangement	Cultivars	Average maturity (days)	Plant population (plants ha^{-1})	Spacing (cm) between rows	Spacing (cm) within rows
Sole crops					
Sorghum	CHS 6	95	180 000	45	12.3
Pearl millet	BK 560	80	180 000	45	12.3
Pigeonpea	ICP 1-6	170	50 000	135	14.8
Groundnut	R-33-1	100	333 333	30	10.0
Intercrops					
2 rows sorghum/			180 000	45	8.2
1 row pigeonpea			50 000		14.8
1 row pearl millet/			50 000	30	15.0
3 rows groundnut			250 000		10.0
5 rows groundnut/			333 333	22.5	11.0
1 row pigeonpea			50 000		14.8
1 row sorghum/			90 000	45	12.3
1 row pearl millet			90 000		12.3

TABLE 2

Description of sites and crop management

Soil	Weed control[1]	Plant protection[2]
1. Deep black soil	Controlled	Intensive
2. Deep black soil	Limited control	Intensive
3. Medium to shallow black soil	Controlled	Economic
4. Deep black soil	Controlled	No protection
5. Deep red soil	Controlled	Intensive
6. Deep red soil	Limited control	Intensive
7. Medium red soil	Controlled	Research
8. Shallow red soil	Controlled	Economic
9. Deep red soil	Controlled	No protection

[1]2–3 weedings were given for complete weed control, as opposed to one weeding in limited weed control.

[2]Crops were sprayed depending on the level of infestation: <5% infestation for intensive protection (usually 3–4 sprays), 5–10% for research protection (usually 2–3), >10% infestation for economic level of protection (usually 1 or 2).

differed in texture, soil depth, weed control, and crop protection provided against insects and diseases (Table 2). The degree of protection varied from intensive to no protection. At one site on each soil type, the trial included the comparison of a weed-free vs. limited weed control. Thus, the systems were evaluated in nine different environments across soil types and crop management level (Table 2). The plot size was 5.4 m×8.0 m; the harvest area for yield was 2.7 m×7.0 m for all the treatments other than groundnut/millet intercrop, which was 2.4 m×7.0 m.

Crop management

Crops on black soils were sown in the dry soil ahead of rains (second half of June), while on red soil they were sown after the rains had wetted at least a 30-cm profile (first half of July). The sites were fertilized uniformly with 18 kg N and 20 kg P ha^{-1} at sowing, and the cereals both as sole crops and in intercropping were later top-dressed with 62 kg N ha^{-1}. A higher seed-rate was used to ensure the required crop stand, and the excess plants were thinned out at about 2–3 weeks after sowing. The sole-crop and intercropping systems were sown in standard row-spacing arrangements using optimum populations (Natarajan and Willey, 1980; Reddy and Willey, 1981; Anonymous, 1983).

Tests for distribution of yields, land equivalent ratios, and income

The distribution of crop yields in both sole cropping and intercropping was examined by Kolmogorov-Smirnov (K-S) statistics (D_{max}; Pearson and Hartley, 1976). After eliminating the differences due to sites, the sole-crop yield residuals were tested for normal distribution, and the intercrop-yield residuals for bivariate normal distribution. In the case of intercrops, the K-S test was applied to the marginal and conditional distribution of yield residuals.

Land-equivalent ratios (LER) were calculated by plot for each intercropping system at each location within a year, using the mean sole crop yields of that location. Land-equivalent ratio is defined as the sum of the sole-crop areas required to produce the same yields as from 1 ha of intercropping (Willey, 1979). Monetary returns were also calculated by plot for each system at each site by partial budgeting, considering the crop prices and input costs as noted in the respective years, and by deducting the variable costs for fertilizer, insecticide sprays, seeds, labour, etc., from the gross value of the respective cropping system. Prices varied considerably from year to year during the experimental period; eg. sorghum was sold at Rs.[1] 0.90–1.50 kg^{-1}, millet at Rs. 1.19–1.35 kg^{-1}, pigeonpea at Rs. 2.6–4.00 kg^{-1}, and groundnut at Rs. 2.5–3.75 kg^{-1}. The K-S test was also applied on monetary returns of the different cropping systems.

Probabilities of minimum crop yields

As farmers are interested in growing more than one crop for family needs, the intercropping should appropriately be compared with a shared sole-crop

[1]The exchange rate between US$ and Rupees during this period varied from 1 US$ = Rs. 7-9.

system containing the two component sole crops grown in a suitable proportion (if one crop occupies s $(0<s<1)$ of a unit area, the other occupies $1-s$). While the farmer has no choice to modify an intercropping system defined for maximum agronomic advantage, he can grow the shared sole in any proportion he desires. Comparison of the intercropping with the shared sole of a fixed proportion as suggested by Rao and Willey (1980) and Shultz (1982) may lead to a bias against the shared system. To avoid such bias, the proportion of two sole crops that has the highest probability of achieving the specified yields was considered as the optimum shared system (Singh, 1987). Let $\bar{A}$ and $\bar{B}$ be yields of sorghum and pigeonpea under sole cropping respectively, and p and q represent a certain proportion of the respective sole-crop yield. If one wants $p.\bar{A}$ of sorghum yield and $q.\bar{B}$ of pigeonpea, then the optimum land proportion of sorghum and pigeonpea in the shared-sole-crop system is the one that gives the maximum value of Prob. (sorghum yield in shared system $\geq p.\bar{A}$, and pigeonpea yield in shared system $\geq q.\bar{B}$). The maximization of the above probability was carried out for several values of p and q $(0<p, q<1)$, and the shared and intercrop systems were compared based on the joint probabilities of achieving those yields.

Probability of income or risk

The shared sole that gives the highest average net return would lead to one of the two (more profitable) sole crops since the return would be a linear function of the proportional crop areas in the shared system:

$$M \text{ (return)} = s \cdot (\text{sole crop } A \text{ return}) + (1-s) \cdot (\text{sole crop } B \text{ return})$$

M would be highest if s is either zero (indicating sole B) or unity (indicating sole A). We, therefore, considered the stochastic shared proportion (optimal sole system), which minimizes the probability of failure to meet the expected net returns. The proportional crop areas vary with the expected net return (M), and beyond a certain level of expected returns even this shared sole is practically the most profitable of the two sole crops. The cumulative probabilities of failure to meet different expected returns by the intercropping and the shared sole were compared for each of the four crop combinations.

RESULTS AND DISCUSSION

The mean yields, land-equivalent ratios, and monetary returns of all the cropping systems, along with the respective standard deviations and K-S statistics, are given in Tables 3, 4 and 5. As the probability level of the observed K-S statistics was more than 0.05 for sole-crop yields and the four intercrop parameters, sole-crop yields can be regarded as normally distributed and the yields in intercropping as bivariate normally distributed for each crop combi-

TABLE 3

Mean yields (t ha^{-1}) of crops in sole and intercropping systems and tests[1] for distribution of yields

Component		Sorghum (A)/ Pigeonpea (B)		Sorghum (A)/ Pearl millet (B)		Groundnut (A)/ Pigeonpea (B)		Groundnut (A)/ Pearl millet (B)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Sole crops									
	A	4.10	1.20	4.10	1.20	1.18	0.68	1.18	0.68
	B	1.23	0.60	2.71	0.68	1.23	0.60	2.71	0.68
Intercrop									
	A	3.38	1.02	1.95	0.67	0.66	0.38	0.74	0.46
	B	0.79	0.39	1.59	0.42	1.15	0.54	1.36	0.55
Correlation (A, B)		0.08		0.02		−0.21		−0.05	
		Kolmogorov-Smirnov Test for Normality (Pearson and Hartley, 1976)							
		D max	P level	D max	P level	D max	P level	D max	P level
Sole crops									
	A	0.50	0.97	0.50	0.97	0.77	0.59	0.77	0.59
	B	0.60	0.86	0.50	0.96	0.60	0.86	0.50	0.96
Intercrop									
	A	0.54	0.94	0.53	0.94	0.64	0.82	0.76	0.62
	B	0.60	0.86	0.58	0.89	0.55	0.92	0.57	0.90
Conditional variables in intercrop									
$Y1 = A$ given B		0.41	0.99	0.52	0.95	0.61	0.86	0.76	0.62
$Y2 = B$ given A		0.74	0.64	0.58	0.89	0.67	0.76	0.71	0.70

[1]The residuals from sole-crop yields were tested for univariate normal distribution and intercrop yields for bivariate normal distribution.

TABLE 4

Land Equivalent Ratios (LER) of different intercropping systems

Component	Sorghum (A)/ Pigeonpea (B)		Sorghum (A)/ Pearl millet (B)		Groundnut (A)/ Pigeonpea (B)		Groundnut (A)/ Pearl millet (B)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Partial LERs								
A	0.82	0.21	0.47	0.15	0.60	0.30	0.68	0.26
B	0.67	0.32	0.60	0.13	0.94	0.39	0.51	0.19
Total LER ($A+B$)	1.49	0.38	1.07	0.13	1.53	0.39	1.18	0.25
Correlation (A, B)	−0.02		−0.53		−0.39		−0.39	

TABLE 5

Income from different sole and intercropping systems and parameters of normality tests

System	Income			K-S statistics	
	(Rs. ha^{-1})	SD[1]	CV (%)[2]	D_{max}	P level
Sole crops					
Sorghum	3848	2264	58.8	0.55	0.93
Pigeonpea	3063	2427	79.2	0.56	0.91
Pearl millet	2195	1029	46.8	0.81	0.53
Groundnut	2798	2512	89.7	0.53	0.95
Intercrops					
Sorghum/Pigeonpea	5367	2519	46.9	0.40	0.99
Sorghum/Pearl millet	3021	1181	39.1	0.57	0.91
Pearl millet/Groundnut	2921	1778	60.9	0.70	0.72
Groundnut/Pigeonpea	4561	2057	45.1	0.71	0.69

[1]Standard deviation.
[2]Coefficient of variation.

nation over the 36 environments. Net-returns data of each cropping system were also normally distributed.

Yields and land equivalent ratios

Sole sorghum averaged 4103 kg ha^{-1} and sole pigeonpea 1226 kg ha^{-1}. The intercrop produced 82% of the sole sorghum and 67% of sole pigeonpea yields, giving an overall land productivity advantage of 49% for the intercrop over sole cropping. As sole crops, both pigeonpea and groundnut were equally productive (groundnut, 1182 kg ha^{-1} and pigeonpea, 1226 kg ha^{-1}). The groundnut/pigeonpea intercropping, with similar temporal difference between the component crops to that in sorghum/pigeonpea, recorded a similar yield advantage (53%) over sole crops, although the proportional crop yields in these systems were different. While the earlier-maturing sorghum in sorghum/pigeonpea was competitive to pigeonpea and contributed a higher proportion of the combined yield, the earlier-maturing groundnut in groundnut/pigeonpea was dominated by pigeonpea and contributed a lower proportion to the combined yield; pigeonpea yields reflected these competitive effects. The high yield advantage in these systems could be attributed to the complementary use of the growth resources such as light, water, and nutrients by the crops over time (Natarajan and Willey, 1981; Anonymous, 1983).

Between the two cereals, sorghum was more productive than pearl millet; however, millet tended to be dominant over sorghum in intercropping, particularly on red soils with limited water-holding capacity (Table 6). The overall

TABLE 6

Land-equivalent ratios of contrasting intercrop systems, according to soil types, weed control, and plant protection

System	Soil type[1]		Weed control[2]		Plant protection[3]	
	Black (16)[4]	Red (20)	Complete (8)	Limited (8)	Protected (16)	No prot. (8)
Sorghum/pigeonpea						
Sorghum	0.92	0.76	0.82	0.85	0.82	0.80
Pigeonpea	0.69	0.65	0.65	0.79	0.59	0.76
Total	0.51	1.40	1.47	1.64	1.41	1.56
Sorghum/pearl millet						
Sorghum	0.52	0.43	0.46	0.50	0.48	0.44
Pearl millet	0.56	0.63	0.56	0.60	0.58	0.64
Total	1.08	1.06	1.02	1.10	1.06	1.08
Groundnut/pigeonpea						
Groundnut	0.59	0.60	0.46	0.49	0.57	0.73
Pigeonpea	1.05	0.84	1.07	1.20	0.90	0.77
Total	1.64	1.44	1.53	1.69	1.47	1.50
Groundnut/pearl millet						
Groundnut	0.61	0.72	0.60	0.82	0.61	0.68
Pearl millet	0.51	0.52	0.58	0.46	0.55	0.49
Total	1.12	1.24	1.18	1.28	1.16	1.17

[1]Soil type: Four sites on black soil and five sites on red soil, over four years.
[2]Weed control: Two sites representing the two soil types for four years for each weeding system.
[3]Plant protection: Five sites across soil types that received some protection in comparison with two sites with no protection over four years. Weed control was similar for both situations.
[4]Numbers in parentheses are observations on which mean values were based.

advantage of sorghum/millet intercropping was small (7%), reflecting the similar growth-patterns of these cereals and the competition between them for resources. Millet intercropped with groundnut yielded twice the expected yield (50% of sole crop against 25% based on sown proportion), and the intercropped groundnut produced about 68% of sole crop compared to the expected 75%, so the total advantage of this system over sole cropping was modest, at 18%.

The relative advantage of sorghum/pigeonpea and groundnut/pigeonpea intercrops was more on black soils than on red soils, primarily due to higher pigeonpea LER (Table 6). Pigeonpea generally grew for 2–3 weeks longer on black soils on account of their higher water-holding capacity. This enabled the intercropped pigeonpea to recuperate from the competition of the associated crop and to produce a high proportion of its sole-crop yield on these soils.

There was no marked difference between the two major soil types for sorghum/millet, but the groundnut/millet system recorded slightly higher LER on red soils, probably because these crops were better adapted to red soils than to black soils. The benefit of intercropping was more under limited weed management, the margin being particularly wider in the case of the two pigeonpea-based systems than with the others. Under limited weeding, the sole-cropped pigeonpea suffered from the competition of weeds and gave low yields, but the intercropped pigeonpea maintained its yields as the associated quick-growing sorghum or groundnut smothered the weeds. Hence the relative yield of pigeonpea was higher, giving a higher yield advantage under this weeding system. Similarly, the groundnut intercropped with millet suffered from weed competition less than the sole groundnut, so that millet/groundnut also showed a slightly higher advantage under limited weeding than under complete weed control. There was no marked difference in the potential benefits of intercropping in respect of degree of plant protection given; only the sorghum/pigeonpea showed a slightly higher benefit under no protection than with protection.

Comparison of intercropping with shared sole cropping

Yields: Intercropping systems were compared with the respective 'shared sole' crops in producing specified yields of both the component crops (Table 7). Table 7 also gives the proportional area for one of the components of the shared soles that achieves the highest probability of the specified yields. The joint probabilities of sorghum/pigeonpea intercropping in producing different quantities of both these crops were higher than those of the shared sole. A farmer who requires both sorghum and pigeonpea for family use would almost always be better-off intercropping them instead of apportioning the area to the two sole crops. The superiority of intercropping to the shared sole came out more clearly as the required crop yields were higher. To cite a few cases, the probability that the intercrop produces 50% of the average sole sorghum and 40% of the average sole pigeonpea yields was 71%, as compared to 37% by the shared sole, and the probability of intercropping succeeding to the extent of 80% of sorghum and 40% of pigeonpea yields was 43%, compared to 8% by the shared sole. Similarly, the probability that one would obtain 50% of pigeonpea and 40% of groundnut yields was 57% from groundnut/pigeonpea intercropping, as compared to only 33% from the optimal shared sole. With groundnut/millet and sorghum/millet, risk from intercropping was less than from the shared sole only over a small range of the specified yields, usually at close to the proportions in which the component crops yielded or were sown in intercropping.

Income and risk: On the basis of average returns, the two pigeonpea-based intercropping systems were more profitable with less-variable returns than either of the respective component sole crops (Table 5). A comparison of the

TABLE 7

Probabilities of obtaining different quantities of specified yields from 'shared sole' and intercrop systems

p[1]	q[1]	Sorghum (A)/pigeonpea (B)			Groundnut (A)/pigeonpea (B)		
		Prop. area[2]	Joint prob.[3]		Prop. area	Joint prob.	
			Shared system	Intercrop		Shared system	Intercrop
0.4	0.4	0.51	0.50	0.75	0.49	0.42	0.60
0.4	0.5	0.48	0.38	0.65	0.45	0.33	0.57
0.4	0.6	0.45	0.28	0.54	0.42	0.25	0.52
0.4	0.8	0.41	0.12	0.30	0.36	0.13	0.41
0.5	0.4	0.57	0.37	0.71	0.53	0.34	0.50
0.5	0.5	0.53	0.26	0.62	0.49	0.25	0.47
0.5	0.6	0.51	0.17	0.51	0.45	0.18	0.43
0.5	0.8	0.46	0.06	0.29	0.40	0.08	0.33
0.6	0.4	0.61	0.25	0.65	0.56	0.26	0.38
0.6	0.5	0.57	0.16	0.56	0.52	0.18	0.36
0.6	0.6	0.54	0.09	0.47	0.48	0.12	0.33
0.6	0.8	0.50	0.03	0.26	0.43	0.05	0.25
0.8	0.4	0.67	0.08	0.43	0.61	0.14	0.19
0.8	0.5	0.63	0.04	0.38	0.57	0.09	0.18
0.8	0.6	0.60	0.02	0.32	0.53	0.05	0.16
0.8	0.8	0.56	0.00	0.18	0.48	0.02	0.12
		Groundnut (A)/pearl millet (B)			Sorghum (A)/pearl millet (B)		
		Prop. area	Joint prob.		Prop. area	Joint prob.	
			Shared system	Intercrop		Shared system	Intercrop
0.4	0.4	0.48	0.51	0.50	0.50	0.59	0.61
0.4	0.5	0.42	0.38	0.36	0.45	0.42	0.49
0.4	0.6	0.38	0.26	0.22	0.42	0.25	0.32
0.4	0.8	0.31	0.08	0.05	0.36	0.06	0.06
0.5	0.4	0.51	0.40	0.43	0.54	0.42	0.39
0.5	0.5	0.45	0.27	0.31	0.49	0.25	0.32
0.5	0.6	0.41	0.16	0.19	0.45	0.12	0.21
0.5	0.8	0.34	0.04	0.04	0.40	0.02	0.04
0.6	0.4	0.53	0.30	0.36	0.57	0.26	0.20
0.6	0.5	0.48	0.19	0.26	0.53	0.13	0.16
0.6	0.6	0.43	0.10	0.16	0.49	0.05	0.11
0.6	0.8	0.37	0.02	0.04	0.43	0.00	0.02
0.8	0.4	0.57	0.15	0.22	0.62	0.07	0.02
0.8	0.5	0.52	0.08	0.16	0.58	0.02	0.02
0.8	0.6	0.47	0.03	0.10	0.54	0.01	0.01
0.8	0.8	0.41	0.00	0.02	0.48	0.00	0.00

[1]p and q are proportions of sole crop yields of A and B, respectively. See Table 3 for sole-crop yields of A and B in each combination.
[2]Proportional area of crop A in optimum shared system.
[3]Joint probability of crop $A \geq p\bar{A}$ and crop $B \geq q\bar{B}$.

cumulative probability distribution curves (Fig. 1) indicates that the sorghum/pigeonpea and groundnut/pigeonpea intercrops were more profitable and less risky than the corresponding optimal sole systems over the entire range of the expected net returns. The magnitude of superiority of intercropping over the sole cropping can be judged from the area between the two curves. Therefore, these two intercropping systems can be recommended to both a risk-neutral (or profit-maximizing) and a risk-averse farmer. These results further confirm the previous observations of Rao and Willey (1980) and Mead et al. (1986) on sorghum/pigeonpea.

Returns from sorghum/millet were intermediate between those of sole crops. They were higher and less variable than those of sole millet but lower and less variable than those of sole sorghum (Table 5). On the basis of risk criterion (Fig. 1), the intercropping had no advantage over the optimal sole-cropping system at the lower end of expected returns, while in fact it was a more risky practice for higher expected returns. Returns from the groundnut/millet intercropping were higher than those of sole millet and were similar to those of sole groundnut (Table 5). The probability curves of the intercropping and the optimal sole system crossed in the middle (Fig. 1), indicating that intercropping had an edge over the best sole crop only in limited situations. Thus, these two intercropping systems did not present strong evidence for reduced risk as compared to shared-sole-crop systems.

Reduced risk from pigeonpea-based intercropping systems was due to the combined effect of higher yields and reduced variability in yields, though it was difficult to separate out how much was due to each of the above factors. Though the yields of the individual components in intercropping showed similar variability to that in the sole system, the combined intercrop production showed less variability than either of the sole crops. Yields from intercropping were particularly less variable under low inputs or unfavourable conditions, as evident from limited weed management, which forms a basis for greater yield stability. Similar results were noted earlier by Rao and Willey (1980) in sorghum/pigeonpea and Francis and Sanders (1978) in maize (*Zea mays* L.)/beans (*Phaseolus vulgaris* L.) in Latin America, where the superiority of intercropping over sole cropping was particularly high under low-input management. The greater temporal difference between the component crops in these systems permitted compensation between them and minimized the variability. The scope for compensation in millet/groundnut or sorghum/millet with similarly growing crops was limited perhaps to situations where one of the crops failed or was affected very early in the season. Considering the case of sorghum/millet, for example, the combined intercrop yields were higher than the highest-yielding sole sorghum only when it was affected by shoot-fly, but even in such cases the total intercrop yields were lower than those of sole millet. That means that a farmer who can quickly substitute millet for sorghum in the event of shoot-fly infestation would realize higher yields than the one who practises

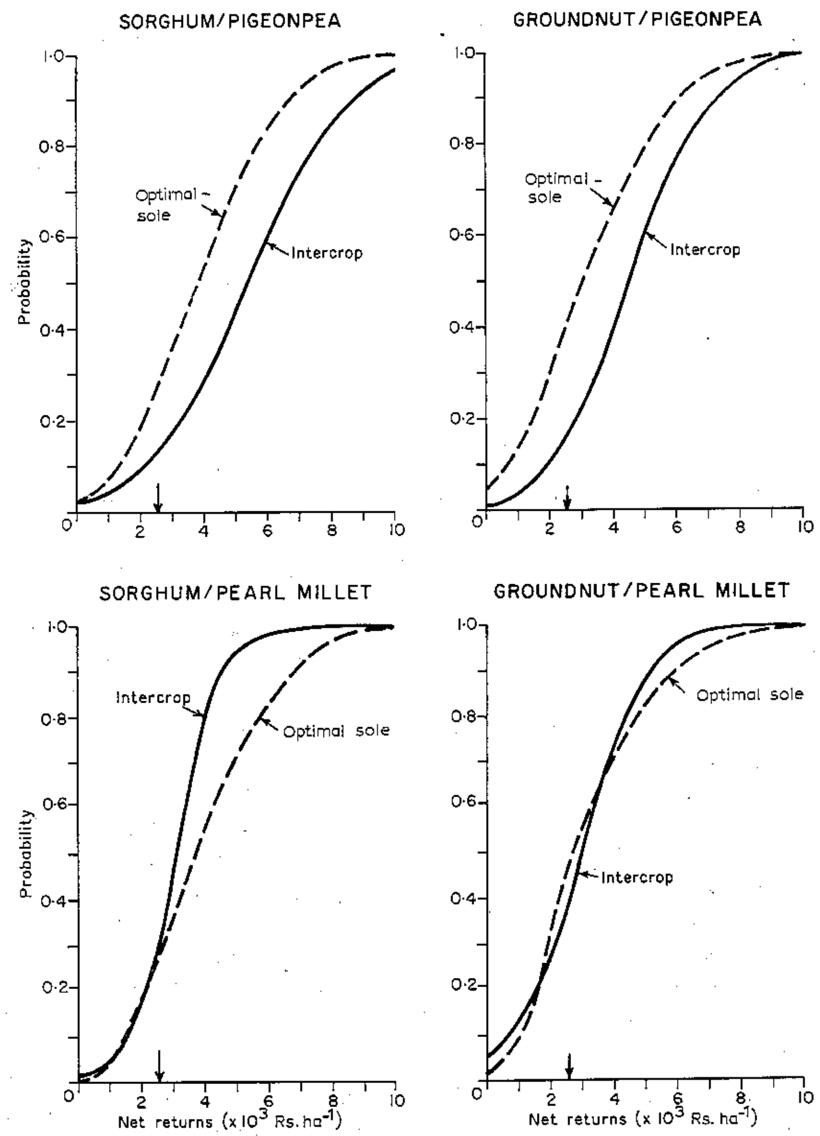

Fig. 1. Cumulative probability distributions of failure to meet expected levels of returns from intercrop and optimal shared sole systems for each of the four crop combinations. (↓ indicates the approximate point below which the optimal sole is a shared sole system, with some of both components, and above which it is practically the sole crop of the most profitable component. (See Table 5 for the most profitable sole crop for each combination).

intercropping. However, practical difficulties may not permit small farmers to resort to crop substitution at short notice, which makes intercropping still an attractive alternative for them. Moreover, intercropping may have the advantage of spreading labour peaks.

This study brings out clearly that reduced risk from intercropping is not universal and much depends on crop combination, cultivars, and agronomic management. Any generalization on intercropping without due recognition of these variables can be misleading. Less risk from pigeonpea-based intercropping systems could be comparable with that of maize/beans in the wetter areas of Latin America (Francis and Sanders, 1978) and intercropping with long-duration sorghums in the Guinea Savanna of Africa (Baker, 1980) and sorghum/maize in Central America (Hawkins, 1984). All these combinations are characterised by large temporal difference between the components and higher total population than in sole cropping, leading to full exploitation of seasonal growth resources and higher yields than the sole crops. On the contrary, intercropping with closely maturing crops such as sorghum/millet and millet/groundnut in this study may not result in marked reduction in risk because of greater competition between components and less overall yield advantage over the sole crops. This was also noted by Rao and Morgado (1984) in maize/beans and maize/cowpea in semi-arid northeast Brazil, where the growing-season was short and the component crops matured within a 3–4-week time difference. However, Singh and Jha (1983) and Mead et al. (1986) reported much lower risk from sorghum-based intercropping with low-canopy legumes such as mung bean (*Vigna radiata* L.), soybean (*Glycine max.* (L.) Merr.), cowpea (*Vigna unguiculata* (L.) Walp) and groundnut in India, where the time difference between the component crops' harvest was generally of the order of 3–4 weeks. Some probable reasons could be that they considered only gross returns, ignoring the cost of additional inputs in intercropping and that their data were based on experiments conducted by different people in widely differing soil and climatic conditions. Evidently, consistent high yield advantage is very important in overall risk reduction. Future studies should consider how the improved agronomic practices affect the risk in promising intercropping systems.

ACKNOWLEDGEMENTS

The authors thank Dr. R.W. Willey (former ICRISAT staff) for suggestions during the conduct of the study and Dr. T.S. Walker for helpful comments in preparation of the paper. They also thank Messrs. M.S. Kumar and P. Keshav Reddy for providing field assistance, P. Venkateswarlu, G. Swaminathan, and V.R. Prabhakar for assistance in computations, and C.P. Jaiswal for secretarial help.

REFERENCES

Anonymous, 1983. ICRISAT (International Crops Research Institute for the Semi Arid Tropics), Patancheru, A.P., India, Annu. Rep. 1982, pp. 272–273.

Baker, E.F.I., 1980. Mixed cropping in northern Nigeria, IV. Extended trials with cereals and groundnuts. Exp. Agric., 16: 361–369.

Evenson, R.E., O'Toole, J.C., Herdt, R.W., Coffman, W.R. and Kauffman, H.E., 1978. Risk and uncertainty as factors in crop improvement research. International Rice Research Institute, The Philippines, Res. Pap. Ser. No. 15.

Francis, C.A. and Sanders, J.H., 1978. Economic analysis of bean and maize systems: monoculture versus associated cropping. Field Crops Res., 1: 319–335.

Hawkins, R., 1984. Intercropping maize with sorghum in Central America: A cropping system case study. Agric. Syst., 15: 79–99.

Mead, R., Riley, J., Dear, K. and Singh, S.P., 1986. Stability comparison of intercropping and monocropping systems. Biometrics, 42: 253–266.

Natarajan, M. and Willey, R.W., 1980. Sorghum-pigeonpea intercropping and the effects of plant population density. 1. Growth and yield; 2. Resource use. J. Agric. Sci., Camb., 96: 51–58, 59–65.

Pearce, S.C. and Edmondson, R.N., 1982. Historical data as a guide to selecting farming systems with two species. Exp. Agric., 19: 353–362.

Pearson, E.S. and Hartley, H.O., 1976. Biometrika Tables for Statisticians, Volume II. Biometrika Trust, University College, London.

Rao, M.R. and Morgado, L.B., 1984. A review of maize-beans and maize-cowpea intercrop systems in the semi-arid northeast Brazil. Pesqi Agropecu. Bras., Brasilia, 19(2): 179–192.

Rao, M.R. and Willey, R.W., 1980. Evaluation of yield stability in intercropping: studies on sorghum/pigeonpea. Exp. Agric., 16: 105–116.

Reddy, M.S. and Willey, R.W., 1981. Growth and resource use studies in an intercrop of pearl millet/groundnut. Field Crops Res., 4: 13–24.

Singh, M., 1987. A stochastic optimum proportion under shared system of sole crops. ICRISAT, Stat. Unit Tech. Rep. No. 6/87, 19 pp. (unpubl.).

Singh, S.P. and Jha, D., 1984. Stability of sorghum-based intercropping systems under rainfed conditions. Indian J. Agron., 29: 101–106.

Schultz, B., 1982. Comparing stability among intercrop and sole crop combinations, with reference to the methods of Rao and Willey, Univ. Michigan, Ann Arbor, 17 pp. (Mimeo).

Trenbath, B.R., 1983. The dynamic property of mixed crops. In: S.K. Roy (Editor), Frontiers of Research in Agriculture. Proc. Symp., 27 September–1 October 1982, at Calcutta, India. Indian Statistical Institute, Calcutta, pp. 265–286.

Willey, R.W., 1979. Intercropping – its importance and research needs. Part 1. Competition and yield advantages. Field Crop Abstr., 32: 1–10.