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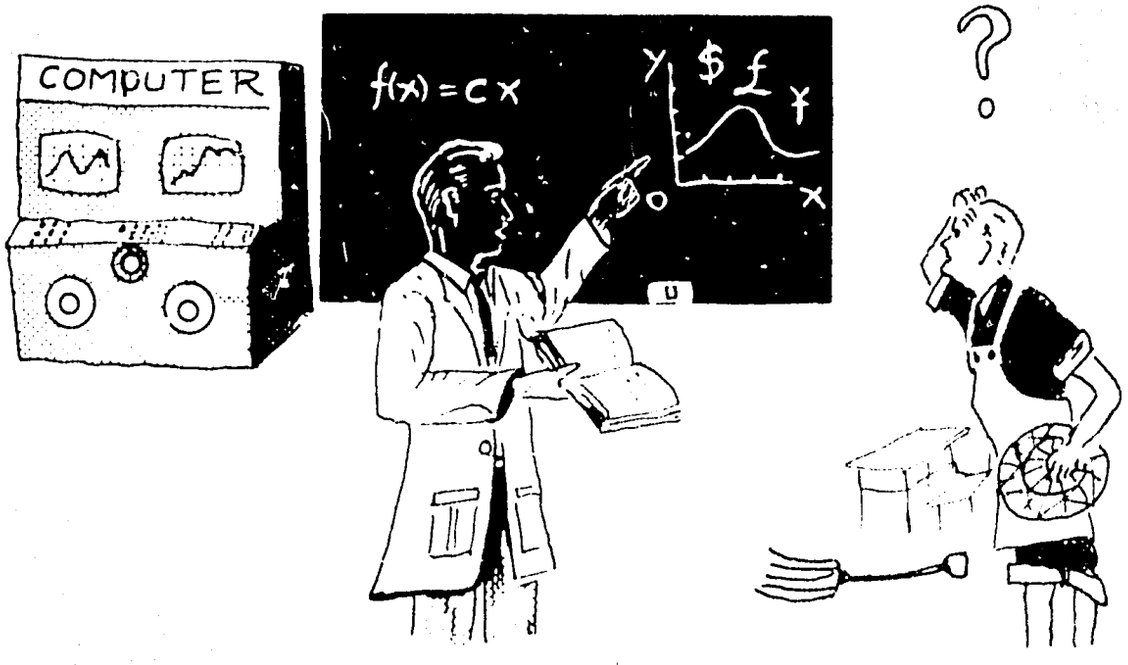

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Four Approaches to Risk and Uncertainty for Use in Farm Management Extension[+]

Peter H. Calkins[++]

The role of farm management researchers and extension personnel is to provide the cultivator with information on new varieties, cropping practices, or farm organization which will help him to improve his well-being. Because of weather uncertainty and other aspects of nature, however, there are few guarantees that an increase in the amount of inputs will lead to a specified level of output. If the farmer decides to adopt a change in his cropping pattern, he must face the additional uncertainty that the recommended changes may not be suitable for his own physical resources and managerial capabilities. This is especially true if only one set of recommendations is given him -- in this case he must make an all-or-nothing choice between adoption and non-adoption, with very little knowledge to appraise the probable increase in his benefits. It is not surprising, then, that many farmers will choose not to adopt the recommended changes.

In his pioneering work *Risk, Uncertainty, and Profit* (1921), Frank H. Knight drew a critical distinction between risk and uncertainty. 'Risk' occurs when the cultivator is aware of the range of possible outcomes from his decision, as well as the probability associated with each outcome.[+++] 'Uncertainty', on the other hand, occurs when the probability of the outcomes or even the outcomes themselves are unknown. It is part of the work of farm management researchers to investigate the probable outcomes of farm management decisions, and thereby to transform unmanageable uncertainty into manageable risk. Agronomic research, in which yields are measured and responses to various levels of inputs and management recorded, tends to generate data from which the risk of an undertaking may be assessed. All too often, however, such types of data are used only to develop a single set of dictates for farmers in a given agro-climatic zone. Even if these farmers cultivate precisely the same soils with precisely the same current productivity, they differ in their attitudes toward risk and uncertainty; this will, in many cases, determine why some farmers adopt new varieties and other farmers do not.

We may conceptualize the farmer's strategy framework as the system of values, goals, decisions, and actions by which the farmer deals with nature on the one hand and society on the other. The farmer's strategies and the actions of nature and government are often different or even in conflict. Moreover, the government may be able to take advantage of conditions which are beyond the farmer's range of action (externalities). These externalities for the farmer may be numerous and significant. Therefore, farmers in general tend to be

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[+++]The farmer's awareness of probability often takes the form of years of experience rather than a mathematical value.

cautious in order to achieve self-preservation. As a result, recommendations for change must probably guarantee high threshholds of benefit before farmers will embark on a new farm management policy.

The literature and other folkways of a society give insight into the values it holds most dear. These tend to be few, however, and range, for instance, from the 'life, liberty, and pursuit of happiness' of American society to the 'long life, health, happiness, wealth, and good fortune' of the Chinese. To either may be added fame, power, and security. The last is extremely important, especially for the farm cultivator, in that it serves as a natural check on the unbridled pursuit of the other values.

Goals may be defined as the tangible embodiment of values. These, too, are often in a state of equilibrium and flux. Thus, the full utilization of land and other resources must often be balanced against a desire for leisure and relaxation, the desire for a rich diet pitted against the complexity and possible unsuitability of self-sufficient farming, consumption in the present weighed against even higher levels of consumption in the future (through present investment), and the desire for higher income balanced against the desire to minimize income variability. How the individual farm operator balances these conflicting goals depends on his perception of his strategy framework. Thus, it is essential for extension agencies to take a full range of potential balancing points into account, since these often determine whether or not the particular cultivator will adopt a given innovation.

The present paper deals with the last trade-off noted: the desire for higher income versus the desire for income stability. Four different methods are presented to take account of possible equilibria between the level of an variability in income. Ways are suggested by which farm management researchers and extension agents may offer cultivators a range of technological options, each with an expected level of income and a prediction of risk. This is done in the interests of promoting maximum adoption of improved varieties.

A set of indifference curves can be developed for the trade-off between income and variance in income (Fig. 1). The ordinate represents expected income and the abscissa, two standard deviations of income. We choose two standard deviations to allow for a reasonable measure of security, because actual income may be anticipated to fall within two standard deviations of the expected income, with a probability of 0.95, or 19 years out of 20. In fact, only the negative value of the standard deviation is important, since the farmer, with fixed debts, obligations and/or others to support besides himself, does not want his income in any year to fall below a certain disaster level. (Income above the expected level may be viewed as good fortune; the more upward the deviation, the better.) For any given farmer, the shape of the indifference curves will differ, depending on whether he is a relative gambler or a relative conservative (Fig. 1), the amount of his fixed costs and obligations, and a host of other factors. For each farmer, there is a set of possible income levels, and with each an associated value of acceptable variance in income. These are plotted as dashed lines in Figure 1. For purposes of comparison, the income lines are the same for each of the two farmers. However, because of differing attitudes towards income and variability, the point at which the gambler will produce has higher income and higher

variance than the point at which the conservative will produce. Thus, the optimum recommendation for each of the two farmers is different. If only one recommendation is made by the extension agent, only one farmer will adopt; whereas, if a whole range of recommendations is made, both farmers will adopt the new technology, though at differing levels.

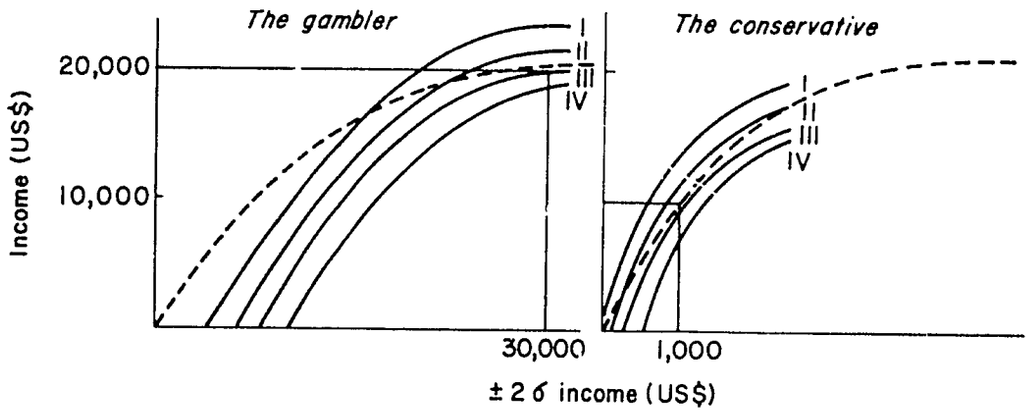

Fig. 1. Income-variance indifference curves compared for gambler and conservative types.

The two farmers represented in Figure 1 are the extreme ends of a whole range of potential attitudes towards expected profit and risk. Thus, if at all possible, a line such as the dashed one in Figure 1 should be approximated by a range of differing recommendations, so that the farmer may choose the coordinates of income and variance with which he personally feels most comfortable. If we speculate that there are six types of farmers, we may develop a set of technologies for each (Table 1). For each of the attitudinal types, ranging from conservative to gambler, the ideal choices of expected income and variance in income are given.

Table 1. Hypothetical preferred income-variance coordinates by farmer type.

Farmer type	Technology level	Expected income	Income variance	Income range[a]
	(6=high)	(US$ 1,000)		
Gambler	6	20	30	(10) to 50
Impetuous	5	18	20	(2) to 38
Bold	4	16	12	4 to 28
Confident	3	14	7	7 to 21
Cautious	2	12	4	8 to 16
Conservative	1	10	1	9 to 11

[a]( ) indicate negative values.

The development of these lists of options is not easy. The type of list formulated depends upon the information available and the level of resources which the research center, or extension agency, or both have at their disposal. Four approaches to developing a frame-

work of risk and uncertainty by which the farmer can make informed decisions on how to modify his farm management operation are presented in Table 2. They may be termed the partial budgeting/minimum returns, the marginal/probability, the linear/quadratic, and the game theory approaches. In general, these represent approaches of increasing mathematical complexity and calculation expense to the research or extension oganization. They do not necessarily carry with them increasing levels of benefit in terms of practical knowledge gained. Even so, all four approaches add new insight into the problems of making farm management decisions under risk and uncertainty and reveal how various researchers have sought to come to grips with the same problem in different ways.

Table 2. Measures of profitability and risk for four methods of analysis.

Analytical method	Measures of profitability	Measures of risk
Partial budgeting/ minimum returns	rate of return no less than 40%	average minimum returns in the worst 25% of trials
Marginal/probability	maximum expected profit through marginal cost & revenue curves	probability distribution of random inputs (sensitivity analysis of prices)
Linear/quadratic	(i) maximum net revenue	(i) price sensitivity analysis & subsistence mentality constraints
	(ii) parameterized net revenue	(ii) minimum solution variance
Game theory	maximax criterion	(i) Wald's maximin criterion (ii) Savage regret criterion (iii) Benefit criterion (iv) Hurwicz-alpha criterion (v) Bayes (Laplace) criterion

Partial Budgeting/Minimum Returns Analysis

Definition: A comparison of the costs and benefits of a recommended practice with existing or other recommended practices under the criteria of overall profitability, return to investment of at least 40%, acceptable minimum returns in the worst 25% of cases and insensitivity to price variations.

Data required: Complete accounts of the levels and prices of the inputs and output of agronomic experiments on a variety of sites (or from year-to-year).

Major benefit: Simple, inexpensive.

Major disadvantage: Generally omits year-to-year variability.

This simple and straightforward approach was formulated by R. K. Perrin, D. L. Winkelmann, E. R. Moscardi, and J. R. Anderson at CIMMYT to better understand and plan for the reactions of farmers to improved wheat and maize varieties developed at that international center (Perrin et al., 1976). The first step is to make a list of technological options open to the farmer and perform partial budgeting analyses of the results of implementing them. As an example, Perrin et al. list the partial budgets of 12 different levels of fertilizer application on maize (Table 3). In partial budgeting, one first lists the yields

and gross revenue from each of the treatment levels, then subtracts from this the variable money costs and the variable non-money (or opportunity costs) of production. This leaves the bottom line of net revenue (net benefit), which allows one to rank the fertilizer levels in terms of their relative profitability. On the basis of this procedure alone, one would likely choose the nitrogen-phosphorus levels 100 and 50 kg/ha, respectively, and advise the farmers to apply fertilizer accordingly.

Table 3. Partial budget of averaged data from fertilizer trials.[a]

Fertilizer treatment N	Fertilizer treatment P_2O_5	Net yield	Gross field benefit[b]	Variable money costs	Opportunity cost[c]	Total variable costs	Net benefit
---(kg/ha)---		(t/ha)	----------(\$100/ha)----------				
0	0	2.0	20	0	0	0	20
50	0	2.8	28	4	0.5	4	24
100	0	3.5	35	8	1	9	26
150	0	3.6	36	12	1	13	23
0	25	2.2	22	2	0.5	3	19
50	25	3.5	35	6	0.5	7	28
100	25	4.0	40	10	1	12	28
150	25	4.4	44	14	1	16	28
0	50	2.1	21	5	0.5	6	16
50	50	3.6	36	9	0.5	10	27
100	50	4.3	43	13	1	14	29
150	50	4.6	46	17	1	18	28

[a]Adapted from Perrin et al., p. 10. Figures do not sum due to rounding off. [b]Gross field benefit in \$/ha at \$1000/t. [c]No. of applications ranged from 0 to 2 with cost/application of 2 days at \$25.

But, as Perrin et al. point out, partial budgeting alone leaves out the problems of both capital scarcity and risk and uncertainty. To analyze the first problem, let us look at the net benefit curve, presented in Figure 2, for various levels of nitrogen and phosphorus. Here we see that, although the 100-50 level of fertilizer application affords the highest net return in dollars per hectare, the return on investment is very low. Indeed, the average rate of return on the first investment of \$700 (elevating fertilizer levels from 0-0 to 50-25) is 114%, while the average rate of return on the second investment of \$700 (elevating fertilizer levels from 50-25 to 100-50) is only 11%. If capital is unlimited and no better investment alternatives exist, the farmer will choose to produce at the 100-50 level of fertilizer application. However, capital is often a constraint in the agricultural households of developing countries, and must be borrowed. Because of interest rates and the cost of loan management, the costs often reach 20% per cropping season. Moreover, Perrin et al. estimate that farmers demand a return for their extra management of about 20%, so that the minimum rate of return on investments in new technology must be 40% before the average farmer will adopt the technology. Thus, the partial budgeting analysis must be modified upward by about 40% before an acceptable level of improved technology can be recommended to the average farmer (see the middle column of Table 2).

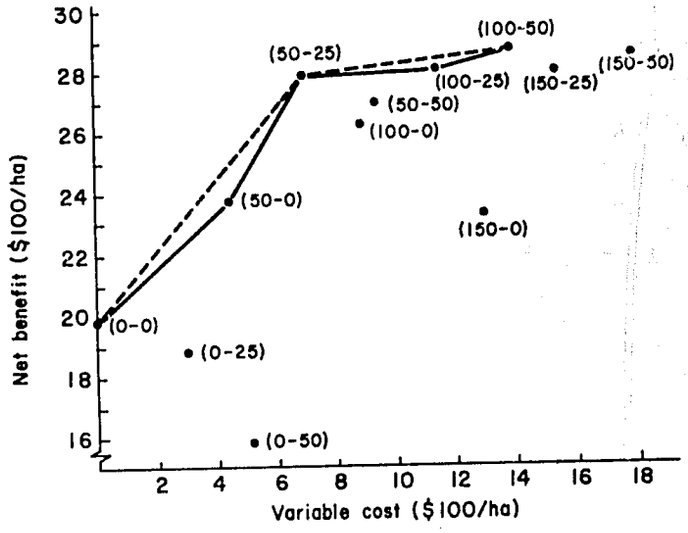

Fig. 2. Net benefit curve for maize fertilizer trials at CIMMYT. Numbers in parentheses represent kg/ha of N and P_2O_5, respectively. Source: Perrin et al., p. 16.

The second problem with the partial budgeting approach is that it ignores the problem of yield uncertainty and risk aversion. For each of the twelve combinations of fertilizer in Table 3, eight replications were performed, and the worst 25% (i.e., the worst two) were evaluated by the partial analysis approach to determine the minimum net benefits from the fertilizer trials. The results of this analysis are presented in Table 4. Here we see that the most favorable average of the worst yields may be obtained from the fertilizer management level 50-25, and that the extra investment of $700 to achieve the highest average net benefit in the 100-50 management level actually results in less favorable worst yields, (i.e., the increase in net revenue also entails an increase in the variability of expected revenue). For the farmer who is dealing with scarce resources at the margin, this is a very important finding.

Perrin et al. suggest a final way to bolster the security of their agronomic recommendations. This is the technique of price sensitivity analysis, which is defined as varying the output or input prices over a reasonable range to ascertain whether the optimum levels of adoption are altered. If they are, then recommendations to farmers must be made with a great deal more circumspection and caution.

Thus, in a few simple steps, Perrin et al. outline a straightforward way to rank the profitabilities of various technological packages, adjust for the scarcity of capital, and consider variability in both yields and prices. The methods they use are clear, straightforward and inexpensive, and are particularly well suited to those research and extension organizations where time and money are especially binding constraints. No attempt is made to quantify the variance of yields and prices or the probability distribution of weather and other natural factors, which are major contributors to yield fluctuations, but for this type of analysis such calculations are not necessary.

Table 4. Minimum net benefits from eight fertilizer trials.[a]

Fertilizer treatments N	P_2O_5	Net benefit worst trial	2nd worst trial	average of worst two
--(kg/ha)--		----------($ 100/ha)----------		
0	0	3.6	10.9	7.2
50	0	6.7	12.8	9.8
100	0	8.7	9.7	9.2
150	0	6.7	7.1	6.9
0	25	4.1	10.8	7.4
50	25	16.2	18.0	17.1
100	25	10.9	16.6	13.8
150	25	9.7	10.9	10.3
0	50	5.1	6.8	6.0
50	50	13.1	21.5	17.3
100	50	15.5	15.9	15.7
150	50	14.6	14.9	14.8

[a]Adapted from Perrin et al., p. 24.

Marginal/Probability Analysis

Definition: An evaluation of the production technology which maximizes expected profit, given the probability distribution of the random input.

Data required: Time series data on the distribution of the random variable and experiments which reproduce that distribution under otherwise controlled conditions.

Major advantage: Takes into account year-to-year variability of random inputs.

Major disadvantage: Requires time-consuming development of experiments which simulate or record random occurrences.

The second approach focuses on the role of nature in upsetting the predictability of yields. Remember that while the goal of the farmer is to minimize variability, nature often operates in a seemingly random way by inflicting drought, floods, winds, extreme temperatures, diseases, insect damage, and animal damage on the farmer's crops at random intervals. Thus, it is quite possible that in the year that the farmer decides to make a large investment in the adoption of improved technology, his whole operation may be wiped out by a natural disaster.

J. P. Doll, V. J. Rhodes, and J. G. West present the marginal/probability analysis approach, which helps to rationalize the confrontation between man and nature (Doll et al., 1968). First, they divide natural occurrences into two categories, risk and uncertainty. Then they point out that occasional occurrences such as the flooding of a river and the death of a prize bull belong to the realm of uncertainty, and can, for practical considerations, be ignored, whereas the amount of rainfall and the incidence of limiting temperatures can be investigated and a probability distribution assigned to them. Confronting these latter variables, then, may become a question of risk and not uncertainty. They further draw the

distinction that the random variable may or may not interact with the controlled inputs which the farmer applies in his management decisions. For example, the amount of plant response to nitrogen, or the effectiveness of an insecticide spraying is often related to the amount of rainfall.

The controlled input and the random input may interact to produce a management problem for the farmer. Ideally, he should use a different amount of input in a dry year, a normal year, and a wet year, but he has no way to tell at planting time what type of year it is going to be. He may apply too little in a wet year and lose in potential product, or he may put on too much in a dry year and lose by over-spending on fertilizer. As noted in Table 2, we are interested in how the farmer can optimize his expected profits while still taking into account the yield fluctuations caused by random inputs from nature. Doll et al. suggest the following procedure:

1) Identify the random input and determine its probability distribution. This requires taking historical data (which may not always be available) concerning the input in question and tabulating the frequency of a given occurrence in quantitative terms. The resulting curve can be depicted as in Figure 3a.

2) Select a range of the controlled input which the farmer might consider. For each use level, compute the marginal cost and marginal revenue curves and the point at which they are equal (i.e., the optimal production technology for all inputs, given the level of the controlled input). The resulting curves are also illustrated in Figure 3.

3) Determine, for each level of the controlled input, the costs and revenues resulting from the random input.

4) Select the amount of the controlled input that maximizes expected profit.

5) If the maximum expected profit selected is less than zero, abandon the enterprise entirely.

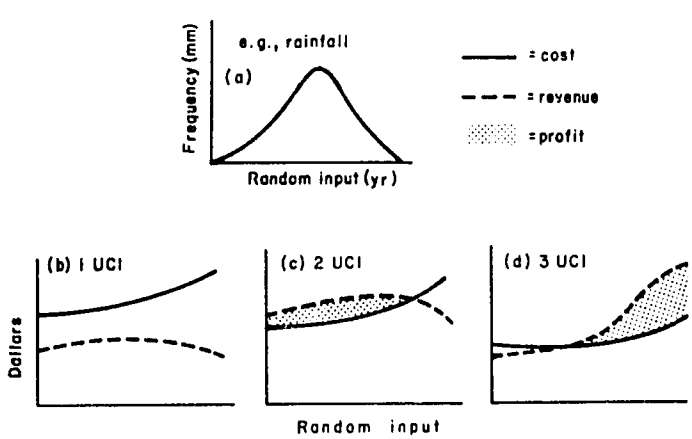

Fig. 3. Probability distribution of cost and revenue functions when random inputs interact with one, two, and three units of controlled inputs (UCI). Source: Doll et al., p. 200.

Doll et al. cite an example in which J. L. Knetsch and W. L. Parks simulate nature's rainfall distribution through irrigation experiments, so that drought ranged from 19 to 73 days. The net returns data from this experiment are presented in Table 5. The expected profits include consideration of the probability distribution, as outlined above, over a reasonable number of years from various levels of fertilizer response and take into account the rainfall distribution. The profit maximizing farmer would choose to apply 150 kg N/ha and would anticipate a loss in one year out of six.

Table 5. Estimated returns per ha after subtracting costs of applying nitrogen (N) at different levels to millet at Ashwood, Tennessee.[a]

Amount of N applied	No. of drought days[b]						Expected profit
	73	56	47	38	29	19	
(kg/ha)			($/ha)				
30	(13)	57	93	123	146	165	95
60	(21)	65	102	133	157	176	102
90	(16)	71	109	140	165	185	109
120	(14)	75	113	145	171	192	113
150	(14)	76	115	148	174	196	116
180	(17)	75	115	148	175	198	116

[a]Adapted from Knetsh and Parks, 1958. Data converted to metric units. Assumed prices are forage, $25/t; N, $0.29/kg; and an application cost of $4.40/ha. [b]Drought days were classified so that each occurs with equal probability, 1/6. ( ) indicate negative values.

However, Doll et al. point out the problem of capital scarcity mentioned by Perrin et al. and note that the more conservative or poorer farmer would probably choose the rate of 90 kg/ha because, by spending $17.40 less on fertilizer, he loses only $6.86 in income. This implies a rate of 39% return on capital investment, which is just below the minimum 40% described by Perrin et al. from their work in Mexico.

The marginal/probability method, like the partial budgeting/minimum returns analysis, provides the farm extension agent with a set of farm recommendations qualified by their relative riskiness. However, the marginal/probability analysis requires not only time series data on the incidence of the random variable in question, but also the conducting of a separate experiment to determine the impact on yields and profits of various levels of the random input associated with various probabilities. While conducting such experiments is within the budget and capabilities of most national programs, this method of developing recommendations is time consuming. Nevertheless, the marginal/probability approach sheds valuable additional light on the year-to-year applicability of results and can augment the findings from the partial budgeting/minimum returns approach, which generally takes into account site-to-site variability in yields. A sensitivity analysis to test the effects of price variation should be conducted in the marginal/probability analysis.

Linear/Quadratic Analysis

Definition: A minimization technique for the variability in expected profit at each of a series of increasing profit levels.

Data required: Precise input-output data on the whole farm enterprise, data on the prices and yields of each commodity in the past and knowledge in the use of computers.

Major advantage: Gives the optimal crop and acreage recommendation for a farm under any specified set of conditions.

Major disadvantage: Volumes of data; high cost in capital and trained manpower.

The first two methods are well suited to the straightforward and low cost development of farm recomendations, but they have two serious drawbacks:

1) They do not take into account the wide range of production alternatives on the farm, the amount of land which should be devoted to each, and the most efficient use of each production input on the farm to yield the maximum revenue.

2) They treat variability of price and yield as separate components, whereas in fact, yield and price interact through supply and demand forces in the market place to determine variabilities in net returns not necessarily correlated with either one.

To solve the first problem, linear programming was developed as a means to farm management decision-making. Without going deeply into the mathematics of the procedure, the linear program seeks to maximize

$$f(x) = cx$$

$$\text{subject to } A_x \leq b$$

$$\text{and } x \geq 0$$

where c = a row vector of enterprise returns net of variable costs

x = a column vector of activity levels in terms of hectares devoted to different crops or units of production

A = a matrix of technical coefficients of enterprise requirements for specific constraints

b = a column vector of resource and enterprise constraints, such as land, labor, and capital.

This is shown diagrammatically in Figure 4. The linear program can be solved by hand, but usually there are so many cropping possibilities and input constraints that an electronic computer is used. The optimal solution which results shows the highest attainable net farm income, subject to the available resources. It also indicates how much land should be devoted to each crop and the marginal value products of all the constraints at the optimal solution (to evaluate whether the operator will gain by expanding his availability of inputs through purchase or hire). Thus, the linear programming solution helps to answer the question of how to maximize expected returns in a way that the other two methods have not been able to.

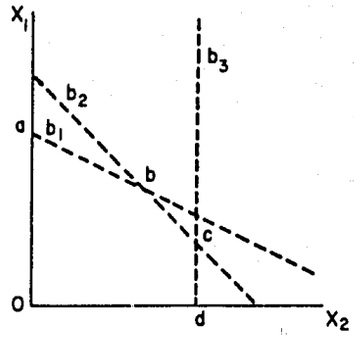

Fig. 4. Iso-resource lines. Source: How and Hazell, p. 6.

But linear programming has been rightly criticized for dictating solutions which are unacceptable to farmers. This is often because the profit maximizing solution is based on the price information of a single year, which may camouflage great variability in expected net returns. Furthermore, the optimal solution tends to prescribe large areas to a small number of crops (or even a grand total of one crop) and to ignore the problems of insects and marketing which may result from overspecialization. Some efforts have been made to correct these deficiencies by:

1) Applying price sensitivity analysis to the inputs and outputs to determine the range over which the optimal solution holds. If this is wide, then the recommendations derived from the linear program may be considered more robust.

2) Including constraints to limit the specialization of land into too few commodities. These so-called 'subsistence mentality constraints' take into account not only the weight of tradition, which serves as a force of security in the farmer's life, but also the desire for a varied diet and for the avoidance of risk in overspecializing even in a very profitable commodity. However, these subsistence mentality constraints are not very scientific as they may cover up entirely new cropping patterns, which not only add substantially to income but also maintain or even reduce current levels of riskiness.

Linear programming can be modified by rewriting the problem as follows:

$$\text{Minimize } f(x) = x' Dx$$
$$\text{Subject to } cx = \lambda$$
$$\text{and } A_x \leq b$$
$$x \geq 0$$

where
- c = a row vector of enterprise returns net of variable costs
- x = a column vector of activity levels
- A = a matrix of technical coefficients
- b = a column vector of constraints
- d = a matrix of variance-covariance terms
- λ = a parameter

The new formulation is called quadratic programming and simply seeks to minimize the variance of the optimum solution, given a minimum level of income as specified by the parameter λ. The parameter λ is simply the income which the simple linear programming

problem sought to maximize. In this way, the quadratic programming approach takes account of both the level of and the variability in income. It develops what are called efficient E-V pairs, i.e., levels of minimum variance (V) for every given level of expected income (E). These E-V pairs form a set of coordinates which may be presented in tabular form, as we shall see later, or plotted as a straight line, as in Figure 5. There, the curved lines represent increasing levels of variance (from left to right) superimposed upon the basic linear programming diagram of Figure 4. If variance in income is of importance to the farmer, he should choose the point along the path where income and variance are most satisfactory to him If capital is not a constraint, he should probably select point P, where the lines of minimum variance meet the production possibility frontier.

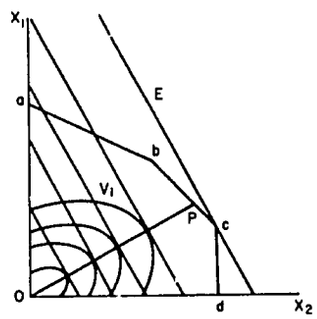

Fig. 5. The quadratic program solution. Source: How and Hazell, p. 11.

How and Hazell have applied both linear and quadratic programming to a fresh market vegetable farm in New York State (How and Hazell, 1963). Table 6 presents the requirements per hectare, the constraint levels of inputs, the optimal planted area to each crop, and gross returns, when the problem is solved using the linear programming approach. The expected net profit under the optimal cropping pattern is $54,354, but the farmer or the extension agent has no way to evaluate the year-to-year variability in net profits.

Table 6. Linear programming model for a vegetable farm in New York State, U.S.A.[a]

Item	Levels of most binding inputs					Values in optimal solution		
	labor				land	level of	gross	gross
	Mar	Jun-Jul	Sep-Oct	Nov-Dec	Sep-Dec	activity	margin	income[b]
	(hr/ha)				(ha)	(ha)	($/ha)	
Cabbage 1	0	20	77	65	1	20	882	17,379
Cabbage 2	1	72	43	3	1	4	981	3,939
Cauliflower	0	38	293	52	1	9	1,135	10,274
Sweet corn	<1	<1	12	2	1	66	286	18,733
Flowers	<1	<1	0	<1	0	6,058[c]	1[c]	3,998
Iceberg lettuce	9	304	0	<1	0	27	1,995	52,978
Other lettuce	34	482	0	1	0	0	3,142	0
Sweet pepper	<1	66	160	<1	1	26	895	231,998
Maximum available	682	11,033	9,228	124		Total:		129,996[d]

[a]Adopted from How and Hazell, pp. 14-15. Data converted to metric units. [b]Less fixed costs, including farm operator's labor. [c]Values for flowers are in crates not ha. [d]The expected net income/ha was $54,354 (see Table 7).

How and Hazell also calculated the gross returns for each of the enterprises over the past eight years. From these data, it was possible to compute not only the variance of each activity but also the covariance of gross margins between any two production activities. How and Hazell found, for example, that variance in gross margin can be greatly reduced by growing two crops such as iceberg early lettuce and other early lettuces in the same year. But what are the levels of expected net income and variance when such combinations are tried? Table 7 lists 10 E-V pairs that might be presented to the farmer for inspection in helping him to choose a farm plan. The linear programming solution, represented as solution 10, gives the highest income, yet it also has a tremendous amount of variance. Thus in some years it might actually yield a net income of -$28,732, a figure within expected probabilities for 19 years out of 20 (i.e., two standard deviations). This level of variability would probably be unacceptable to most cultivators. The farm operator seeking stability would probably choose solution 9, which guarantees him a positive income of at least $9,700 in 19 years out of 20 and gives him an expected long run net income of only $3,000 less than that of solution 10. The main difference between the two solutions is that in solution 10, a full 26.5 ha of early iceberg lettuce are planted, while in the more stable solution of 9, 7.7 ha of iceberg and 11.8 ha of other early lettuces are planted. Also, fewer crates of flowers, which have a positive correlation with iceberg lettuce, are produced.

Table 7. Expected income and standard deviations for efficient net income-standard deviation pairs, quadratic programming results.[a]

E-V solutions	Expected net income	Standard deviation	Two standard deviation range	
			lower limit	upper limit
	($)			
1	(47,992)	1,611	(51,144)	(44,700)
2	(7,864)	6,183	(20,228)	4,500
3	(783)	7,250	(15,283)	13,717
4	2,499	7,842	(13,185)	18,183
5	7,083	8,731	(10,379)	24,545
6	32,325	14,305	3,716	60,936
7	49,956	19,872	10,212	89,700
8	51,372	20,621	10,130	92,614
9	51,817	21,070	9,677	93,957
10	54,354	41,543	(28,732)	137,440

[a]Source: How and Hazell, p. 19. ( ) indicate negative values.

By taking into account the variability in both prices and yields (which are combined into gross returns), the quadratic solution has advantages over the partial budgeting/minimum returns and marginal/probability analyses. It is also able to determine exact planted areas under plans with different pairs of expected income and variance of income. However, the demands of the quadratic programming approach are also great. Successful calculation requires accurate historical data on costs and yields, the time and training of a skilled analyst, and the expense and accessibility of a computer. Thus, in development

situations where money, experitise, and time may be lacking, it is doubtful whether the benefits of such on approach exceed the costs. Nevertheless, many developing countries are conducting farm record keeping studies which would provide the raw data for measuring the impact of a reallocation of resources on a farm. If a computer terminal is available and representative farms can be pinpointed for large numbers of target farmers, the use of quadratic programming may be an especially valuable tool in guiding farmers toward cropping patterns that increase their income and maintain or decrease riskiness.

Game Theory

Definition: A comparison between the levels and variability of benefits derived from adopting various decision-making criteria in games with nature.

Data required: Time series data on the economic returns from various technologies over time (or from site-to-site).

Major advantage: Allows for the rationalization of a farmer's approach to nature.

Major disadvantage: Theoretical, must usually be calculated by computer.

A fourth way to study the trade-off between the levels of and variability in expected income is through game theory. This approach emphasizes the fact that nature is an unpredictable combatant. Indeed, a whole school of game theory has been called 'games against nature'. There are a number of decision criteria by which the farmer can attempt to get the better of nature, a few of which are listed in Table 2. As a point of departure, let us look at the *maximax criterion*. This is not seriously considered by most players of game theory, because it simplistically dictates that the player choose the strategy which yields the single highest level of profit in some year, and gives no weight to average, expected, or minimum benefits. In this sense it is the analog of the pure profit maximizing criteria outlined by the partial budgeting, marginal, and linear programming approaches and, as such, casts light on how inadequate pure profit maximization may appear to the farmer. Only the complete gambler would ever consider such a strategy.

Other decision criteria, however, take risk into account in more rational ways. The first is Wald's *maximin criterion*, which looks at the worst possible outcome for each of a number of strategies and chooses the best one among them, disregarding the maximum or average benefits expected from each strategy. This is obviously the decision of a farmer who always fears the worst from nature (which may not be entirely justified), and represents an extreme version of the minimum returns analysis put forward by Perrin et al. who average the worst 25% of the yields and also account fully for significant improvements in the expected level of net returns.

A third decision criterion is the Savage *regret criterion*. This rule endeavors to protect the player from the cost of mistakes. In each row, the maximum loss is identified, and that strategy is finally selected which contains the smallest maximum regret element. This strategy has been criticized for giving a higher ordinal ranking to strategies which may have countervailingly lower levels of overall benefit. Thus, it is not entirely appropriate for the general farmer. A slight modification to the above is the *criterion of benefit*. This rule maximizes the benefit over the worst choice of strategy. The worst possible

result in every case is noted and then the degree of improvement which each strategy affords is calculated. The strategy which gives the highest return in the case of the worst possibility is chosen.

The *Hurwicz-alpha criterion* proposes a weighted average of the minimum and maximum payoffs of each strategy. Thus, if the farmer chooses to let alpha equal 0.6, he would rank his minimum payoff of any strategy 0.6 and the maximum payoff 1-0.6=0.4. However, the Hurwicz criterion also ignores intermediate values.

Finally, there is the *Bayes or Laplace criterion*, which says that if we have no knowledge concerning the probability distribution of the outcomes, we must rank them all equally and determine the average expected value. This criterion has the advantage of taking into account the intermediate values of the strategy, but it also suffers in that the simple act of classifying priorities is quite arbitrary. This criterion can be improved upon by having the player (or the farmer) subjectively rank the probabilities of nature's possible strategies. In the case of an old and experienced farmer, such an approach might prove extremely valuable.

To reveal how subjective the game-theory approach is, let us take the maximum and minimum yields from the Perrin et al. data on maize net returns and enter them into a simple two-by-two matrix. Strategy A (50-25 levels of fertilizer) has two payoffs, $2,790 and 1,620/ha, while strategy B (100-50 levels of fertilizer) has two different payoffs, $1550 and 2870 (Fig. 6). Different game theory criteria dictate different indifference curves, as introduced in Figure 1, and these in turn dictate different strategies as being optimal. Thus, for example, under the maximax criterion strategy A is better; under the maximin and Bayes criteria, strategy B is better; and under the Hurwicz-alpha criterion (if alpha is greater than 0.52), strategy A is superior. Mixed strategies are also possible. This exercise clearly shows that even when the payoffs from the strategies are known, the choice of optimal strategy depends entirely upon the psychology of the farmer.

Strategy A (50 kg N, 25 kg P)	2790	1420
Strategy B (100 kg N, 50 kg P)	1550	2870
	I	II
	Payoff	

Fig. 6. A game theory diagram for Mexican maize yield. Adapted from Baumol (1965) and Perrin et al. (1976).

Donato Antiporta has made an interesting application of some of the above strategies to a study of varietal and management strategies for rainy and dry season grain production in India. Table 8 lists the optimum cropping and fertilizer program under the Wald's

Table 8. Optimal crop and nitrogen (N) fertilizer combinations for Delhi State, India, using the various decision models.[a]

Decision model	Crop[b]	Nitrogen	Optimal combination
A. Dry season:		(kg/ha)	(%)
Wald's maximin	Wheat (LR)	80	100
Savage regret	Wheat (KS)	80	70
" "	" (KS)	120	30
Benefit	" (LR)	80	27
"	" (LR)	120	37
"	" (KS)	80	18
"	" (KS)	120	19
B. Wet season:			
Wald's maximin	Sorghum	150	2
" "	Millet	40	98
Savage regret	Sorghum	150	65
" "	Millet	40	35
Benefit	Maize	150	51
"	Sorghum	150	27
"	Millet	40	22

[a]Adapted from Antiporta, p. 166. [b]LR = Lerma Rojo and KS = Kalyan Sona which are improved wheat varieties.

maximin, the Savage regret, and the benefit criteria. Antiporta notes that the benefit decisions are always combinations of the other two models. However, the benefit decisions are not as profitable in the long term. Table 9 lists the total expected payoffs from the mixed cropping plans. The Savage regret criterion gives higher yields than the Wald's maximin, which in turn out-yields the benefit criterion. But the rankings differ between rainy and dry seasons, and one would be hard put to say that the expected profits of any strategy are always superior to the others. It is evident, however, that the variability in income is greatest from the Savage regret matrix, and that this might make a marginal farmer reluctant to use this criterion for decision making.

Table 9. Expected payoffs from mixed cropping plans for Delhi State, India, for four crop years.[a]

Decision model	Crop year				Payoff	
	1964-65	1965-66	1966-67	1967-68	ave.	total
A. Dry season:	($/ha)					
Wald's maximin	118	244	401	159	230	922
Savage regret	23	202	624	371	305	1220
Benefit	80	234	483	255	263	1052
B. Wet season:						
Wald's maximin	339	464	339	413	389	1555
Savage regret	274	367	517	387	386	1545
Benefit	249	299	406	421	344	1375

[a]Adapted from Antiporta, p. 167. Conversion rate: Rs 7.50 = US$ 1.

The above results are all derived from linear programming algorithms. Antiporta finally suggests that it is possible to develop a modified Hurwicz-alpha plan whereby the crops are grown at various percent levels of the available land in any given season, dictated by the area of the optimism index over which they are optimum as a pure strategy (Table 10). This device permits one to avoid the use of the computer and is also possible without a long series of yield data.

Table 10. Optimal crop and nitrogen fertilization rate combinations corresponding with various optimism indices in Delhi State, India.[a]

Crop	Variety	Amount of N	Domain of optimism	Composition of modified plan
A. Dry season:		(kg/ha)		(%)
Wheat	Lerma Rojo	60	0 to 0.16	16
"	Sharbati Sonora	100	0.16 to 0.20	4
"	Sonora 64	120	0.20 to 0.49	29
"	Kalyan Sona	120	0.49 to 1	51
B. Wet season:				
Millet	Hybrid HB-1	40	0 to 0.39	39
Sorghum	CSH-1	150	0.39 to 1	61

[a]Adapted from Antiporta, p. 168.

Consequently, game theory is also able to reflect the farmer's preferences for expected income against the possibilities of substantial variation in income. An extension agent could present the various options contained in Tables 8 through 10 to the farmer, ask which level of returns he would prefer to have and then explain to him the cropping plan which would allow him to approximate it most closely. However, while game criteria allow for the rationalization of a farmer's approach to nature, they are generally too theoretical and abstract for the average farmer or extension agent to become interested in or confident about. They also require time series data on the economic returns from various technologies over time, which may be beyond the capabilities of the average research institute, and they must also be calculated by computer (except in the case of the modified Hurwicz-alpha criterion). Thus, except perhaps in the case of the last, the use of game theory in farm decision making must remain a curiosity which enriches our understanding of the possible ways to view man's interactions with nature, but which has little practical application.

Conclusion

The first three means of analysis(partial budgeting/minimum returns, marginal/probability, and linear/quadratic approaches)are all valuable tools for taking account of risk and uncertainty in the preparation of alternative technological packages which may be offered to the farmer. The most practical, straightforward, and inexpensive approach is partial budgeting/minimum returns analysis, so that, if resources are limited, this approach seems most appropriate. The other two approaches are able to shed more time-series information on the variability in incomes which the farmer must face, and hence are valuable supplements to the first approach, if resources permit. A country's research and extension program could investigate technological change through all three means, in order to develop technologies which could offer farmers of varying psychological or managerial disposition a means to enhancing the level and stability of their income.

Marvin W. Kottke, in his 1961 article 'Budgeting and Linear Programming Can Give Identical Solutions', has further suggested that, even if there is a linear programming facility in a given country, budgeting is better for studying economies of size, for determining partial or small overall adjustments, and for reporting to the farmer the otherwise unintelligible results of linear programming. Having made a major adjustment through linear programming, the farmer can update this decision by slight modifications of the partial budgeting format into which it has been coded. Linear programming can be used as a mean for suggesting initial major adjustments, for serving as a referral option for future problems beyond the capabilities of budgeting analysis, and for computing price sensitivity maps.[+]

Through one or all of the above approaches, research and extension personnel can provide the cultivator with vital knowledge of the level and variability of his net returns. Only then will the farmer be able to translate his previous uncertainty into identifiable risk.

[+]These show the ranges of input and output prices over which given solutions are optimal.

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