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Incorporating risk in the economic analysis of agronomic trials: fertilizer use on barley in Syria

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ABSTRACT

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In the drier areas of Syria yields of barley, the principal crop, are low. Due to the variability in rainfall, fertilizer use is perceived as risky. Barley-fertilizer trials have been conducted on farmer's fields over a period of four years to investigate whether the large yield response to fertilizer observed on research sites could be achieved under farmers' conditions. Data were pooled across years and sites and response functions estimated.

Simple optimization analysis shows that economic optimum fertilizer rates vary considerably with rainfall and relative prices. Historical rainfall data are combined with the estimated response functions, and stochastic dominance analysis is used to compare the riskiness of fertilizer treatments in terms of net benefits and benefit–cost ratios. Results show that, given the estimated expected rainfall in barley producing areas, fertilizer use, especially at low levels, may not be as risky as has been believed. Extensions of the methodology to include other environmental variables, or to target recommendations, are discussed.

INTRODUCTION

In the drier areas of Syria, receiving 200–350 mm annual rainfall, barley (*Hordeum vulgare* L.) is the principal crop, grown primarily for livestock feed. Diagnostic surveys have found that barley grain yields average about 500 kg/ha (Mazid and Hallajian, 1983) and that only about 10% of farmers use fertilizer on barley (Somel et al., 1984). Due to the low and variable rainfall, fertilizer use in these areas is perceived as risky, and supply and credit policies have not encouraged its use.

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Research by the Farm Resource Management Program (FRMP) of the International Center for Agricultural Research in the Dry Areas (ICARDA) has found that yields are low, not simply because of the low rainfall, but because the low availability of nutrients in the soils in these areas prevents the efficient use of the rain that does fall. On many farmers' fields, only 15% of the rain received is used by the crop, the remainder being lost to evaporation from the soil surface (ICARDA, 1986). ICARDA has investigated the possibility of increasing crop water use efficiency through the application of fertilizer. Results from research station trials over a range of seasons and sites across northern Syria showed that fertilizers increased water use efficiency by around 75% (Cooper et al., 1987; Shepherd et al., 1987).

In 1984, FRMP and the Soils Directorate of the Syrian Ministry of Agriculture and Agrarian Reform initiated a collaborative project with the objective of assessing the biological effectiveness and economic viability of fertilizer use on barley in dry areas. Barley fertilizer trials were conducted in farmers' fields over a period of four years, to investigate whether the large yield response to fertilizer obtained on research stations could be reproduced under the highly variable soil and rainfall conditions faced by farmers. Detailed agronomic analyses of the results from these trials are presented elsewhere (SD/ICARDA, 1990; Jones and Wahbi, 1991). In this paper we extend the economic analysis of these results to assess the risk involved in the use of fertilizer on barley in dry areas.

In assessing the economic viability of fertilizer use and in developing appropriate recommendations for farmers, due account must be taken of farmers' objectives and the conditions in which farmers operate.

Response to fertilizer under farmers' conditions

A total of 75 researcher-managed trials were conducted over a period of four years (1984/85–1987/1988) in farmers' fields at sites throughout the barley areas of northern Syria. Sites were selected each year to represent the range of rainfall, the main soil types, natural soil fertility, and the predominant crop rotations – barley-fallow and continuous barley – in the area (Jones and Wahbi, 1991). The majority of sites were on soils belonging to three main soil types: Xerochrepts, Calciorthids and Gypsiorthids. Soil fertility was measured by the initial soil content of mineral-N (ppm in the top 40 cm of soil) and Olsen-P (ppm in the top 20 cm of soil). Levels of mineral-N ranged from 4.9 to 27.6 (excluding one site at which levels exceeding 200 ppm were recorded) and levels of Olsen-P ranged from 2.2 to 11.5. Rainfall was measured at each site; total seasonal rainfall ranged from 136 to 568 mm.

TABLE 1

Estimated response functions

Independent variables	Fallow–Barley		Barley–Barley	
	Coefficients	SE	Coefficients	SE
N	−2.037	2.988	0.289	3.755
P	7.556 **	1.992	6.047 *	2.503
R	22.459 **	0.860	24.945 **	1.091
N^2	−0.0752 *	0.035	−0.1117 *	0.046
P^2	−0.0532 **	0.016	−0.0408 *	0.020
R^2	−0.0263 **	0.001	−0.0310 **	0.001
NP	0.0632 **	0.019	0.0263	0.024
NR	0.0299 **	0.006	0.0506 **	0.008
PR	0.0013	0.004	−0.00013	0.005
Constant	−2394.17 **	152.66	−3238.14 **	197.32
Adj. R^2	0.605		0.656	
F	294 **		143 **	

** indicates significance at the 1% level, * at the 5% level

Each trial consisted of two replicates of a randomized complete block design with four rates of nitrogen (0, 20, 40, 60 kg/ha of N) and four rates of phosphate (0, 30, 60, 90 kg/ha of P_2O_5). Data were pooled across years and sites and the following response function was specified (Jones and Wahbi, 1991):

$$Y = b_0 + b_1N + b_2P + b_3R + b_4N^2 + b_5P^2 + b_6R^2 + b_7NP + b_8NR + b_9PR \quad (1)$$

where Y is grain yield (kg/ha); N nitrogen applied (kg/ha N); P phosphate applied (kg/ha P_2O_5); and R total seasonal (Oct.–April) rainfall (mm). There were significant rotation effects in the response of barley to fertilizer, therefore the response functions were estimated separately for barley following fallow (F–B: 54 sites) and barley following barley (B–B: 21 sites). These are given in Table 1.

In both rotations the response to N is strongly rainfall-dependent as indicated by the large positive coefficients on the NR interaction terms, while the interaction between P and rainfall is weak. Under the fallow–barley rotation, there is also a strong interaction between N and P so that the marginal response to N increases with P and vice versa. Under the barley–barley rotation, however, this relationship is weaker.

The significantly large positive linear response to P compared to the non-significant coefficient on the linear N term, combined with the smaller

coefficients on the quadratic term for P should be noted. This, along with the low interaction with rainfall, means that response to P is largely rainfall-independent as will become clear later. This low interaction between P and rainfall also means that N makes a relatively greater contribution than P to the marginal response to rainfall:

$$\text{(F–B)} \qquad \partial Y/\partial R = 22.5 - 0.05R + 0.03N + 0.001P$$

$$\text{(B–B)} \qquad \partial Y/\partial R = 24.9 - 0.06R + 0.05N - 0.0001P$$

Farmers' objectives

In the dry areas of northern Syria, barley is grown primarily to provide feed for the farmer's own livestock (sheep and goats). Thus, it is assumed that farmers aim to maximize their output of barley, while at the same time minimizing the risk of loss of return on their investment in inputs. In maximizing output a farmer is minimizing the amount of supplementary feed otherwise needed to be purchased. In modelling the response of barley to fertilizer use, we have used barley grain as the measure of output. This does not mean that farmers are not interested in their straw yields; straw is a very important additional source of feed in these areas and, especially in dry years, can have considerable market value. However, including straw would involve the estimation of joint production functions and greatly complicate the analysis. So, for the purposes of this paper, as an example of a methodological approach, our attention is limited to barley grain.

Under the low and variable rainfall conditions prevailing in the area farmers tend to minimize risk of financial loss by producing barley with the minimum of inputs. Few barley producers in these dry areas use fertilizer. The adoption of fertilizer would therefore involve the investment of a farmer's limited capital resources in what is perceived as a risky, and expensive, input. Following Perrin et al. (1974), a farmer is unlikely to accept a new technology unless he is assured of some minimum average return on his investment. However, the minimum rate of return acceptable to a farmer is itself a function of the farmer's attitudes toward risk. According to Dillon and Hardaker (1984), it "is generally accepted that the rate of return to farmers on their working capital over the cropping season should be at least 40%, of which half is an allowance for risk". Perrin et al. (1974) acknowledge that the figure of 40% is a 'rule of thumb' but is consistent with behaviour observed among farmers in less developed agricultural areas. They also note, however, that for subsistence farmers in areas with high yield variability, the minimum acceptable rate of return is

likely to be higher. Thus, in subsequent analysis in this paper, as a 'rule of thumb' a minimum acceptable rate of return is taken to be 50%.

Economic optimum rates of fertilizer

Economically optimal rates of N and P are found by maximizing the net gain to fertilizer use. Net gain is the difference between the value of output and the variable costs associated with fertilizer use. In this paper we use the prevailing price of barley grain to value grain output. This is the price a farmer would have to pay to purchase barley for feed rather than producing his own. Variable costs associated with fertilizer use include the cost of the fertilizer, transportation and application costs, and the cost of harvesting. The cost of harvesting is included because yields vary with fertilizer rate, and in Syria most harvesting is done by contracted combine harvesters at a charge of 10% of the yield. Thus net returns to fertilizer can be expressed as:

$$\text{net return} \qquad Z = Q_Y(Y - 0.1Y) - Q_N N - Q_P P$$
$$= 0.9Q_Y Y - Q_N N - Q_P P \tag{2}$$

where Q_Y is price of barley grain; and Q_N, Q_P cost/kg of nutrients N and P_2O_5, respectively, where costs include transport and application costs. Economic optimum rates of N and P are those that maximize net return such that:

$$\partial Z/\partial N = \partial Z/\partial P = 0$$

or

$$0.9\ \partial f(N, P, R)/\partial N = Q_N/Q_Y \qquad \text{and} \quad 0.9\ \partial f(N, P, R)/\partial P = Q_P/Q_Y \tag{3}$$

where $f(N, P, R)$ expresses yield as a function of N, P and rainfall, R, as in equation (1), and Q_N/Q_Y and Q_P/Q_Y are the relative costs of N and P_2O_5, respectively. Thus, economic optimum rates of fertilizer are a function of relative costs and rainfall. Economic optima have been estimated for a range of relative costs and rainfall and are presented in Table 2 for the two rotations.

Table 2 also gives the net benefits and benefit–cost ratios associated with the estimated optima. Net benefit (BEN) is the change in net return from applying fertilizer compared with no fertilizer:

$$\text{BEN} = 0.9Q_Y(Y_{NP} - Y_{00}) - (Q_N N + Q_P P) \tag{4}$$

TABLE 2

Estimated economic optima, by rainfall and relative prices

Relative price of $N\&P_2O_5$	N^* P^* BEN BCR						
	Barley–Fallow						
5	0 11 16 29	0 20 22 22	11 29 29 15	25 37 55 18	38 46 100 24	52 55 164 31	66 63 247 38
4	0 31 46 37	13 40 57 27	27 48 87 29	40 57 135 35	54 66 202 42	68 74 288 51	81 83 393 60
3	15 51 95 48	29 59 128 48	43 68 180 54	56 77 250 63	70 85 340 73	83 94 448 84	97 103 575 96
2	31 70 178 88	45 79 234 94	58 88 308 105	72 96 401 119	85 105 513 134	99 114 643 151	113 123 792 168
1	47 90 298 217	60 99 375 236	74 108 472 260	88 116 587 288	101 125 721 319	115 134 874 352	128 142 1045 386
	Barley–Barley						
5	12 10 14 13	23 13 54 29	35 17 120 46	47 21 213 63	59 24 333 80	70 28 479 97	82 32 653 115
4	18 25 46 27	30 29 101 43	42 33 183 61	54 36 292 81	65 40 427 101	77 44 589 122	89 48 778 142
3	25 41 101 51	37 45 172 70	49 49 269 92	60 52 393 116	72 56 544 141	84 60 722 167	96 63 926 194
2	32 57 179 101	44 61 265 127	56 64 378 157	67 68 517 191	79 72 684 227	91 76 877 263	103 79 1096 301
1	39 73 279 250	51 76 381 300	62 80 508 357	74 84 664 420	86 88 846 487	98 91 1054 558	109 95 1290 631
Rainfall (mm)	150	200	250	300	350	400	450

N^*, P^* economic optima for given rainfall and relative costs;
BEN net benefit (kg/ha grain equivalents) from applying N^* and P^*
BCR net benefit–cost ratio (%)

where Y_{NP} is yield (kg/ha) with fertilizer rates of N and P, and Y_{00} yield without fertilizer. Dividing by Q_Y, we can express net benefit in kg/ha grain equivalents, i.e. in terms of physical output:

$$\text{BEN}(\text{kg/ha}) = 0.9(Y_{NP} - Y_{00}) - (Q_N/Q_Y \cdot N + Q_P/Q_Y \cdot P) \quad (5)$$

The benefit–cost ratio (BCR) is the ratio of the change in net returns to the change in costs associated with applying fertilizer:

$$\text{BCR}(\%) = \text{BEN}/(Q_N N + Q_P P) \times 100 \quad (6)$$

From Table 2 it is clear that optimal rates of N and P_2O_5 (N^* and P^*) increase with rainfall and decline with relative costs, as would be expected. N^* is more sensitive to changes in relative costs under the fallow–barley rotation – at low relative costs N^* (F–B) exceeds N^* (B–B), while at high relative costs the situation is reversed. P^* is always higher under the fallow–barley rotation.

Net benefits, for any given rainfall and relative cost, are higher under the barley–barley rotation, except at the lowest rainfall (150 mm). This is because the optimal rates of N and P, and thus costs, are lower under the barley–barley rotation, and the difference between fertilized and unfertilized yields are higher. Consequently, benefit–cost ratios also tend to be higher under the barley–barley rotation.

In 1989/90 the relative costs for N and P_2O_5 were $Q_N/Q_Y = 2.351$ and $Q_P/Q_Y = 2.484$. The mean rainfall over all sites and years in the trial was 284 mm. At these relative costs and rainfall, optimal rates are 65 kg/ha N and 90 kg/ha P_2O_5 under fallow–barley, and 63 kg/ha N and 63 kg/ha P_2O_5 under barley–barley. These approximate to the highest fertilizer rates included in the treatments in the trial. At higher rainfall levels, and at lower relative costs, the estimated economic optima exceed these levels, implying considerable extrapolation of the response function.

From the estimated response functions we have determined optimal fertilizer rates. This analysis is, however, essentially static and deterministic: because the optimal rates vary considerably, depending on rainfall and relative prices, it is useful only when prices and rainfall can be specified. Furthermore, examination of the data revealed that rates of N and P substantially lower than the economic optima yield net benefits of almost the same magnitude. This implies that as rates approach the optima, the marginal rate of return to an additional kg of fertilizer is negligible.

No recommendations can be made based on this type of analysis unless it is assumed that the farmer has full foreknowledge of the rainfall and prices that will occur in the growing season. While a farmer may have some knowledge of relative costs prior to fertilizer application and may adjust his usage accordingly, he has no foreknowledge of how much rain will be received. Basing recommendations on estimated optima for some specified

average or representative rainfall ignores the variability that is one of the main sources of risk facing farmers.

To develop recommendations appropriate to farmers' conditions, we must take account of this variability in rainfall. To do so, we return to the treatments included in the trials and examine how these perform given the distribution of rainfall in the drier zones of northern Syria.

RISK ANALYSIS

The risk associated with applying fertilizer on barley in dry areas can be attributed to two sources: yield variability and price variability. Yield variability is a function of both environmental variability (primarily rainfall) and variability in agronomic conditions, including the rates of fertilizer applied. The latter is the focus of this paper: to determine the best combination of fertilizer to apply given the uncertainty relating to prices and rainfall. In Syria, prices of both fertilizer and barley grain are controlled by the State and for the purposes of this paper are regarded as fixed, and variability in rainfall is taken to be the main source of risk facing farmers.

Seasonal (September to August) rainfall data, for the years 1959/60 to 1985/86, from 25 meteorological stations in the barley growing areas of Syria were used to estimate a representative 'expected rainfall' for each of

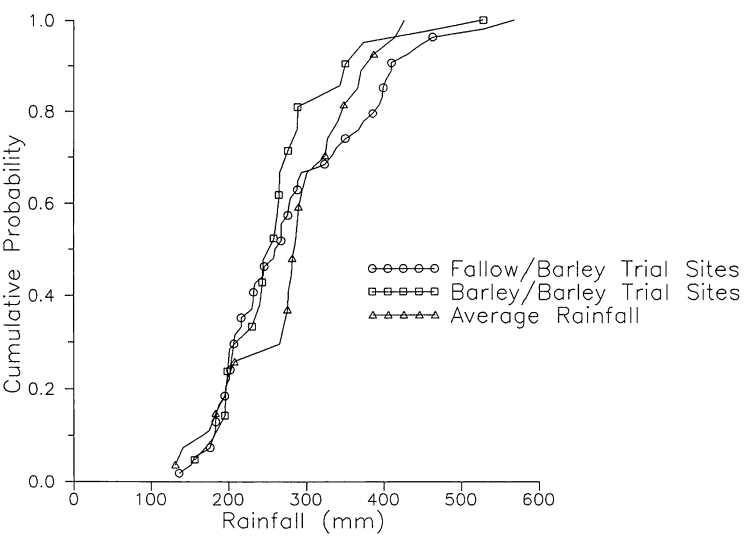

Fig. 1. Cumulative distributions of rainfall at trial sites compared with estimated expected rainfall in barley producing areas.

the 27 years. Figure 1 shows that the cumulative distribution of these averages is very similar to the rainfall received in the 75 sites in the trial. [1] The distribution of the estimated expected rainfall has a slightly higher probability of extremely low rainfall occurring and a lower upper limit (approximately 450 mm). The long tails of higher values rising to over 550 mm in the distributions for the trial data derive mainly from the exceptionally wet 1987/88 season (SD/ICARDA, 1990).

Substituting the estimated expected rainfall into the response function in equation (1), yields were predicted for each of the 16 treatments in the trial for each of the 27 years. Then, based on these predicted yields, and using relative prices for N and P of 2.351 and 2.484, respectively, net benefits and benefit–cost ratios were estimated according to equations (5) and (6). The resulting cumulative distributions of net benefits for each treatment are shown in Figs. 2 and 3 for fallow–barley and barley–barley, respectively. [2] Means and standard deviations are given in Table 3.

As noted earlier, the response to P in the absence of N is more or less independent of rainfall. Consequently, in Fig. 2 net benefits from using P alone are low but highly stable as indicated by the near vertical distributions for N_0P_{30}, N_0P_{60}, and N_0P_{90}. In contrast, use of N without P results in highly variable net benefits as shown by the slopes of the distributions for $N_{20}P_0$, $N_{40}P_0$, and $N_{60}P_0$ in Fig. 2. Moreover, the higher the rate of N when $P = 0$, the higher the probability that net benefits will be negative. These three treatments also give the lowest mean returns (Table 3). Similarly, under the highest rate of N and lowest rate of P ($N_{60}P_{30}$), there is about 18% probability that net benefits will be negative. These four treatments can therefore be eliminated from further consideration under the barley–fallow rotation.

Of the remaining treatments, net benefits increase with the various combinations of N and P, especially in response to increases in N (compare distributions within each level of P in Fig. 2). However, variability in net benefits (as measured by the standard deviation) also increases more or less linearly with increases in N and P (Table 3).

In the barley–barley rotation, the response function predicted negative grain yields at the lowest levels of expected rainfall which lie outside the experimental range. [3] When calculating net benefits these negative yields

[1] In estimating cumulative probability distributions it is assumed that each rainfall has an equal probability of occurring.

[2] For reasons of space the full results for benefit–cost ratios are not presented. However, they are compared with the results for net benefits later in the analysis (see Fig. 4).

[3] The lowest expected rainfalls were 131 mm and 141 mm, compared with the lowest rainfall recorded in the barley–barley trials of 156 mm.

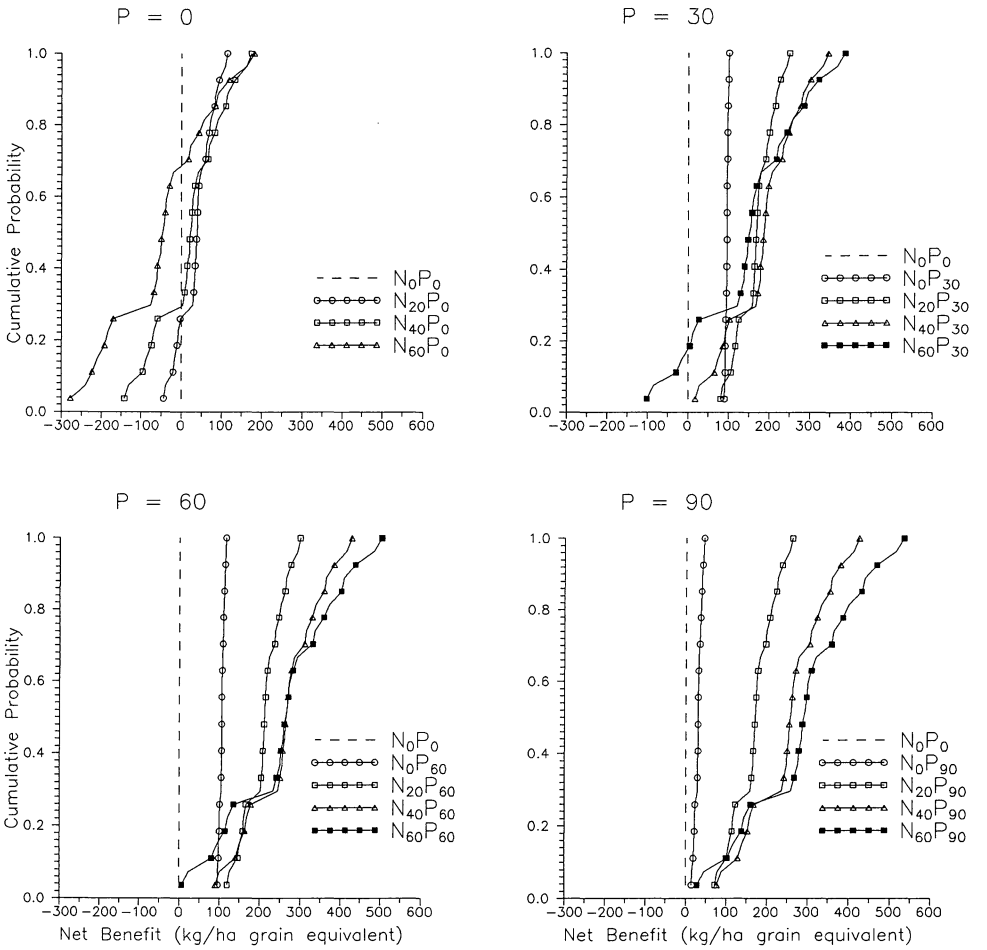

Fig. 2. Cumulative distributions of net benefits (kg/ha grain equivalents): barley–fallow rotation.

were set to zero. In these cases, net benefits represent a 100% loss of investment in fertilizer, i.e., the benefit–cost ratio = −100%. As a result, in Fig. 3 all treatments display some probability (about 10%) of loss in net benefits. Otherwise, results are similar to those for fallow–barley but with some important qualifications.

The upper tails of the distributions, and the mean net benefits (Table 3) are much higher than under fallow–barley, particularly for the higher combinations of N and P. Again, net benefits from applying P alone are highly stable, but are lower than in fallow–barley and at the highest level of P (N_0P_{90}) they are negative over the full range of average rainfall.

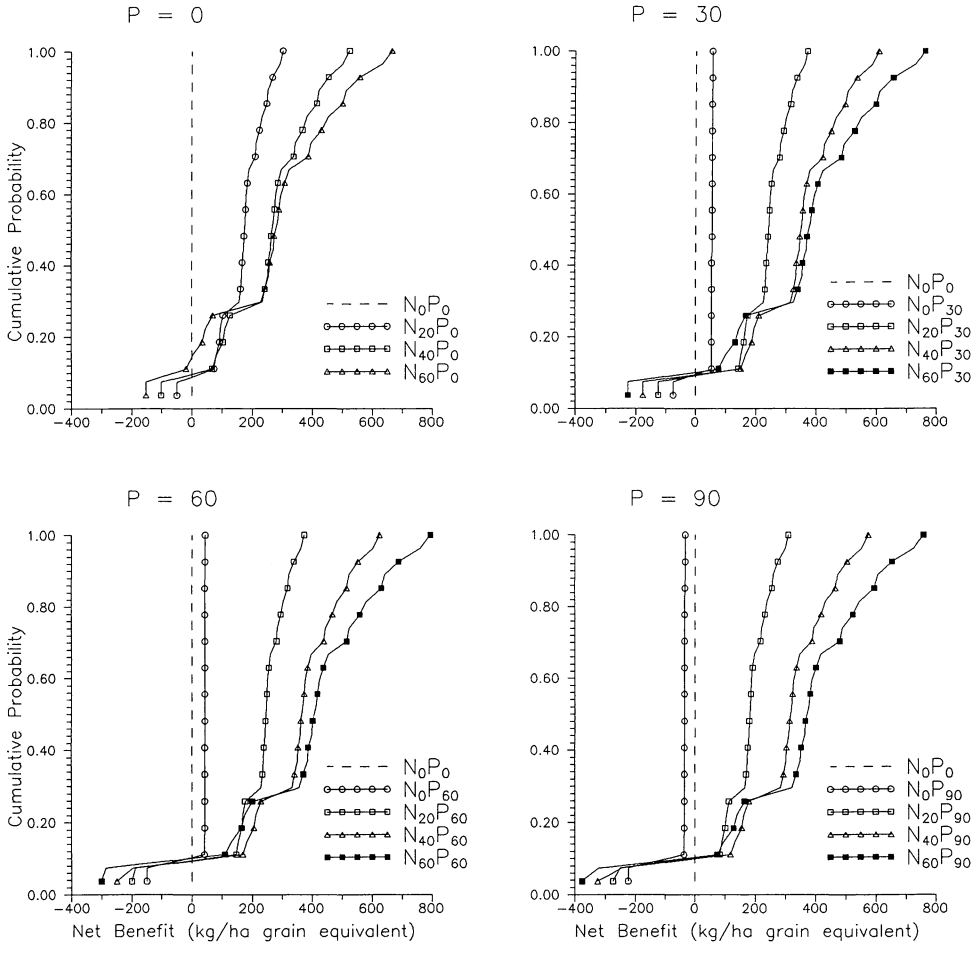

Fig. 3. Cumulative distributions of net benefits (kg/ha grain equivalents): barley–barley rotation.

Applying N alone, on the other hand, is not as 'risky' as in fallow–barley (see $N_{20}P_0$, $N_{40}P_0$, and $N_{60}P_0$ in Fig. 3 compared with Fig. 2).

The question remains as to how we select among the distributions. It is often posited that farmers prefer stability of yields to more variable yields. However, as can be seen from Figs. 2 and 3, there are occasions when more variable returns may be preferred to more stable but lower yields, e.g. at $P = 90$, the distributions of net benefits from high rates of N would be preferred to N_0P_{90} by anyone who prefers more to less. Selecting between many of the treatments involves a trade-off between lower but more stable distributions and more variable distributions that give some probability of

TABLE 3

Means and standard deviations for predicted distributions

Treatment	Fallow–Barley				Barley–Barley			
	Net benefit		Benefit–Cost ratio		Net benefit		Benefit–Cost ratio	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
N_0 P_{30}	96.3	2.7	103.0	2.6	45.1	33.8	49.6	42.3
N_0 P_{60}	106.5	5.4	60.0	2.8	29.0	50.4	16.1	32.8
N_0 P_{90}	30.5	8.1	12.1	3.2	−48.2	49.6	−20.4	22.5
N_{20} P_0	38.1	41.5	58.0	65.9	165.7	85.1	209.0	104.9
N_{20} P_{30}	168.5	44.2	106.1	24.9	224.0	115.0	131.1	71.7
N_{20} P_{60}	212.8	46.9	86.3	17.4	221.5	131.3	86.6	55.9
N_{20} P_{90}	170.9	49.6	52.6	14.5	157.8	132.5	47.0	43.6
N_{40} P_0	22.0	83.0	13.3	73.2	257.0	155.6	170.1	100.7
N_{40} P_{30}	186.6	85.7	84.8	36.4	328.4	185.0	134.8	78.4
N_{40} P_{60}	265.0	88.4	85.3	26.2	340.6	198.4	103.4	63.1
N_{40} P_{90}	257.2	91.1	65.5	21.8	290.6	201.1	71.0	52.2
N_{60} P_0	−46.2	120.8	−34.6	78.2	273.8	214.2	125.9	98.4
N_{60} P_{30}	150.5	127.2	53.7	45.3	358.4	242.2	115.7	79.7
N_{60} P_{60}	263.1	129.9	71.0	33.3	382.3	260.4	96.3	68.2
N_{60} P_{90}	289.4	132.6	63.5	27.7	346.0	264.1	72.2	58.1

considerably higher returns. The best combination of N and P depends on where these crossovers occur and what criteria are used to evaluate the trade-offs.

DECISION MAKING CRITERIA

Decision making under uncertainty involves choosing between alternative courses of action (fertilizer rates) whose outcomes are determined by the state of an uncertain environment (rainfall). Under the expected utility hypothesis, the optimal action is that which maximizes expected utility (Anderson et al., 1977). Empirical application of expected utility maximization requires knowledge of the probability of occurrence of the possible environmental states and the utility associated with each outcome. This approach assumes that preferences are completely known and that a single-valued utility function can be specified. This is rarely the case in practice; eliciting accurate information on risk preferences is difficult and subject to error, and preferences are not unique across decision makers.

Other approaches to decision making have compared minimum returns, selecting the activity that maximizes the minima (the maximin criterion), or selecting the activity that minimizes the probability of returns falling below some specified disaster level (safety-first criterion). Both these approaches

embody implicit assumptions regarding decision makers' attitudes towards risk.

In the absence of complete information on risk preferences, other ordering criteria have been specified. Such criteria provide a partial ordering of alternatives by identifying a set of risk efficient activities, given certain restrictions placed on the set of utility functions of a group of individuals.

One of the simplest and most widely used approaches to efficiency analysis is the expected return–variance (EV) approach. Despite its widespread application, however, there are some important objections to the EV criterion. First, it equates risk with variance which means that extreme gains, as well as extreme losses, are considered undesirable. There may be cases where an increase in variance is not undesirable, for instance if it is accompanied by an upward shift in the location of the distribution (Bailey and Boisvert, 1989). Second, the EV approach is consistent with the expected utility hypothesis only when utility can be specified as a function of the mean and variance only. This occurs when outcomes are normally distributed, whatever the form of the utility function (Anderson et al., 1977, pp. 192–193) or, regardless of the distribution of outcomes, if a quadratic utility function is assumed. The assumption of normally distributed outcomes is unrealistic in many cases, while the quadratic utility function exhibits increasing absolute risk aversion, a theoretically unacceptable restriction to place on preferences (Bailey and Boisvert, 1989).

The development of the theory of stochastic dominance has provided an alternative approach to efficiency analysis that is consistent with the theory of expected utility maximization but does not require explicit knowledge of preferences. Risk efficient activities are identified, according to restrictions placed on risk preferences, by comparing the probability distributions of outcomes.

Under the theory of stochastic dominance, first degree stochastic dominance (FSD) represents decision makers who simply prefer more to less (no restrictions are placed on risk preferences). Activity A is preferred to activity B by FSD if the cumulative probability of A is less than or equal to the cumulative probability of B with the inequality holding for at least one level of return. More simply, this means that the cumulative distribution of A must equal or lie to the right of (exceed) that for B. For instance, in Fig. 2, $N_{20}P_{60}$ dominates N_0P_{60} by FSD.

FSD is unable to rank distributions that cross. Second degree stochastic dominance (SSD) can be used to eliminate some of the activities that cannot be eliminated by FSD, but it also embodies further restrictions on decision makers' risk preferences: SSD represents decision makers who prefer more to less and who are also risk averse. Activity A is preferred to

activity B by SSD if the area under the cumulative distribution of A never exceeds, and somewhere is less than, the area under the cumulative distribution of B, i.e., if the area between the two distributions above the crossover point exceeds the area between them below the crossover point. For instance, in Fig. 2, $N_{60}P_{60}$ dominates N_0P_{60} by SSD.

RESULTS

Stochastic dominance analysis was carried out for the cumulative distributions of net benefits and benefit–cost ratios. The results from SSD were no different to those from FSD (except in one case: benefit–cost ratios in fallow–barley when SSD eliminated one further treatment). Consequently, in Fig. 4 we present the results for FSD, thus placing no restrictions on farmers' risk preferences: the set of treatments identified by FSD are appropriate for risk takers (gamblers) as well as those who are averse to risk.

In the fallow–barley rotation, FSD reduced the choice of treatments to three for both net benefits and benefit–cost ratios. However, the two sets contain very different treatments. Looking at net benefits first, treatment $N_{60}P_{90}$ dominates the other treatments in about 70% of years, but this has to be balanced against the almost negligible returns to this treatment in low rainfall years. Of the other two treatments, $N_{20}P_{60}$ would be preferred to $N_{40}P_{60}$ in only about 15% of years, and then only marginally. $N_{40}P_{60}$ may thus represent the 'best bet' when net benefit is the choice criterion.

If the benefit–cost ratio is used as the decision criterion then the situation is very different. The FSD set contains the three lowest treatment combinations of N and P. Of these $N_{20}P_0$ can be eliminated as it has about a 30% probability of yielding negative returns (and in fact this is the treatment that was eliminated by SSD). The choice reduces to N_0P_{30} versus $N_{20}P_{30}$. The crossover occurs at about 30% cumulative probability. N_0P_{30} yields a benefit–cost ratio of between 120% and 135% over all years, while $N_{20}P_{30}$ involves a trade-off between lower returns in about one-third of the years and equally higher returns in another third of the years. There is little difference between the two distributions in the remaining years. Any choice between the two treatments depends on how far farmers value the stability of returns to their investment in fertilizer. Furthermore, the trade-off depends crucially on the minimum rate of return acceptable to farmers. If this was increased from 50% to 100%, for instance, then N_0P_{30} would be preferred.

Under barley–barley, stochastic dominance was not as efficient in reducing the choice of treatments due to the many crossovers between distributions. FSD reduced the choice according to net benefits to eight treatments, and for benefit–cost ratios to five treatments. In contrast to the

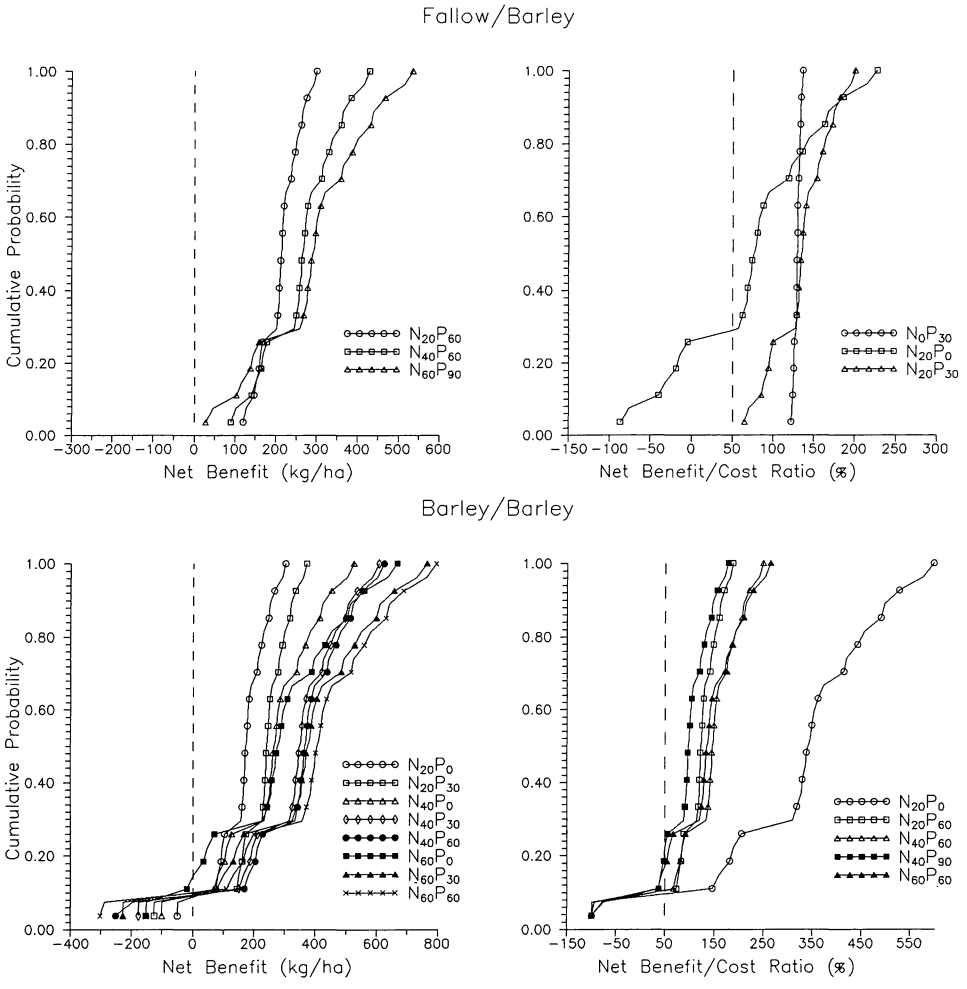

Fig. 4. Risk-efficient treatments by first degree stochastic dominance: net benefits v. benefit–cost ratios.

fallow–barley rotation, there is some overlap between the two sets. Again looking at net benefits first, all treatments have approximately 10% probability of yielding negative net benefits, except $N_{60}P_0$ for which the probability of loss is higher. If we minimize the size of the loss involved (akin to the maximin criterion) then the lowest treatment, $N_{20}P_0$, would be preferred. However, this also gives the lowest net benefits in the remaining years. There is very little to choose between the other treatments.

Looking at the benefit–cost ratios, the situation is much clearer. Of the five treatments, the highest combinations of N and P, $N_{40}P_{90}$ and $N_{60}P_{90}$,

have higher probabilities of yielding benefit–cost ratios below 50%. Of the other three treatments $N_{20}P_0$ is clearly dominant, lying well to the right of the others. So, while $N_{20}P_0$ may give some of the lowest net benefits, the low costs associated with this treatment translate into benefit-cost ratios that are significantly higher than other treatments.

CONCLUSIONS

By incorporating historical data on rainfall with response functions estimated from on-farm trial data we have been able to assess the riskiness of fertilizer use under farmers' conditions.

Based on these results we can offer some general recommendations for fertilizer use in the drier areas of northern Syria. Under a barley–barley rotation, combining the results for net benefits and benefit–cost ratios, treatment $N_{20}P_0$ would appear to be the most efficient choice. Under a fallow–barley rotation, the results are not as clear, differing according to the decision criterion used: if net benefit is the criterion of choice then $N_{20}P_{60}$ or $N_{40}P_{60}$ would be recommended, while for the benefit-cost ratio the choice lies between N_0P_{30} and $N_{20}P_{30}$. Without further knowledge of farmers' objectives and decision making criteria we cannot make any firm recommendation.

These results serve to demonstrate that, given our estimated expected rainfall conditions over 27 years, fertilizer use, especially at low levels, is not as risky as has been believed. Under barley–barley there is some risk of losses from investment in fertilizer, but this might be attributed to the poor performance of the estimated response function in predicting yields at low rainfall levels outside the range received in the trials. This is an unavoidable fact of conducting trials in variable environments: even with multiple site, multiple season trials one is not assured of obtaining results that represent the full range of variable environmental conditions.

The results in this paper depend crucially on the specification of the distribution of rainfall. We used the average of the recorded rainfall from 25 meteorological stations to represent the variability in rainfall in the barley growing areas of northern Syria. In reality, wetter zones of the area are likely to have a higher probability of higher rainfall and drier zones a higher probability of low rainfall. A change in the distribution of rainfall translates into a change in the distribution of net benefits (or benefit–cost ratios) and, more importantly, where the crossovers between distributions occur.

Furthermore, stochastic dominance analysis places great emphasis on the lower, left-hand tails of the distributions: under FSD and SSD, the lower bound of a dominant distribution cannot be less than that of a

dominated distribution, or, a dominant distribution cannot have a greater probability of the worst possible outcome than a dominated distribution. Thus, the results will be very sensitive to changes in the lower extreme values and their associated probabilities. However, it can be argued (Bailey and Boisvert, 1989) that this is precisely the area of the distributions that risk averse farmers are most concerned with, i.e., the risk of some disastrous outcome occurring. While wetter zones of the area may have higher probabilities of higher rainfall, given the highly erratic nature of rainfall in this region, there may still exist a small probability of a very low rainfall occurring.

It is stressed that these are generalized results based on generalized response functions that include only seasonal rainfall as an environmental variable. No account is taken of the distribution of rainfall within seasons. Similarly, the site to site variability in soil type, depth, and inherent soil fertility (available N and P) has not been included. The general recommendations above apply to a broadly defined environment. Specialized recommendations could be made for more specifically defined environments by estimating response functions separately for soil types (as was done for the two rotations), or by including soil fertility parameters in the model. Locationally specific recommendations could be generated by using historical rainfall data for specific locations rather than the averages over a range of locations used in this paper.

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