Production response and input demand in decision making: nitrogen fertilizer and wheat growers

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Abstract

The use of economic analysis to aid farm input investment decisions has been contentious because of observed flatness of economic response in the region of the optimum input. In this paper an application of a crop simulation model, to specify the production response, in conjunction with production economic theory has been used to develop fertiliser input demand functions. These have been combined with return on investment criteria in a graphical presentation for wheat growers in making nitrogen fertilization decisions at a particular location. The approach provides objective information to which growers can apply their own subjective preferences in making fertilizer input decisions.

Introduction

The use of economic analysis to develop farm management recommendations, especially relating to livestock stocking rates and farm input levels, has been contentious for farm management economists, agronomists and extension officers. In particular, invoking the profit-maximization assumption has been of concern. The flatness of economic response near the optimum input means that there may not be a great cost in recommending a sub-optimal (in profit terms) level (i.e. in being roughly right). In contrast, the strict application of that assumption in a world of uncertain agricultural outcomes and a variable trading environment may lead to recommendations that are probably wrong for a risk-averse decision maker (i.e. being precisely wrong). Agricultural economists have developed areas of theory and methods of analysis which have addressed the risk issue (utility analysis (Dillon 1971), risk analysis (Anderson *et al*. 1977, Hardaker *et al*. 2004)). The question discussed here is whether there is another way of developing farm input recommendations that provides valuable information to decision makers in an investment context.

In this paper I investigate the use of economic analysis to provide information to wheat growers when considering Nitrogen (N) fertilizer inputs. The argument draws on results of a particular analysis (Farquharson 2004) to make some general points about the use of input demand functions and return on investment (ROI) criteria for risk-averse farmers. I present a graphical display of marginal conditions for alternative crop outcomes (according to climatic variation) as an aid to decision making.

Background

The debate between Jardine (1975) and Anderson (1975) illustrated the phenomenon of insensitivity of farm enterprise profit to the agricultural input level. Jardine (1975) noted for stocking rate production functions that two-thirds of the optimal stocking rate yielded about 90% of the optimal gross margin. Further he argued that farmers would choose to operate at sub-optimal levels to cope with uncertainty and provide more management flexibility. Anderson (1975) stated that agricultural economists had long known of this characteristic and asked the question of why a farmer would choose the 90% level over some other.

Perrin (1976) investigated the value of information and theoretical models in crop response research. He noted that use of a linear response and plateau (LRP) production function provided a biological basis for the flatness of economic response when considering the optimal input level. There has been debate about crop response functional forms between the agronomic (LRP) and economic (smooth concave functions) points of view (eg Ackello-Ogutu *et al*. 1985). There are implications from this choice for the shape of the response function and the degree of substitutability between two or more nutrients. Berck and Helfand (1990) resolved the functional form question by illustrating that the effects of spatial variability in soil conditions (i.e. across a field) and temporal variability in crop planting and flowering dates resulted in an LRP form for individual plants and a concave response in the more general case. France and Thornley (1984) noted that many biological relationships are of this latter form.

Pannell *et al*. (2000) discussed the incorporation of risk into farm modelling and considered that an emphasis on algebraic modelling was unfortunate because assessing responses to risk is primarily a numbers game, which varies from one situation to another. They found that, because of the flatness of economic response, considering complexities such as risk aversion resulted in changes in the optimal strategy which did not greatly affect farmer welfare. Malcolm (2004) considered that decision makers faced with risk (the case where probabilities can be estimated and risk analysed) and uncertainty (where no probability estimates are possible and uncertainty cannot be analysed) were constrained by what is known or knowable. If decision makers' goals are modified in response to the existence of uncertainty, then the extent of this modification is determined by their perception of where the decision lies on the continuum from risk to uncertainty, and their attitudes to these circumstances. In these situations he recommended an exploration of the consequences of a small number of discrete scenarios encapsulating significant combinations of events. Risk could be analysed using information about probability distributions where judgements can be formed about such distributions. 'Appreciation of risk and uncertainty and its management is aided in all manner of ways by more information and by greater clarity of communication about risk and uncertainty' (Malcolm 2004, p. 413).

Pannell (2006) discussed some consequences of flat payoff functions in economic decision making, including that decision makers often have a wide margin for error in their production planning decisions, that optimising techniques are sometimes of limited practical relevance for decision support, that the value of information used to refine management decisions is often low, and that the benefit of using 'precision farming' technologies to adjust production input levels are often low. This paper attempts to illustrate a case where the use of optimising techniques can provide relevant information for decision support where the value of information may be high.

The economics of optimum fertiliser input levels has been discussed by Kennedy *et al*. (1973), Stauber *et al*. (1975), Godden and Helyar (1980), and Kennedy (1981). Helyar and Godden (1977), Battese (1978) and Helyar and Godden (1978) debated the issues relating to biological response functions, residual fertiliser effects in future decision periods, and incorporation of stochastic effects. The suitability and use of dynamic programming for this issue was set out by Kennedy (1981). Rather than consider issues of response and carryover, the question here is how to present results from those analyses in a decision-making context.

Issues for decision support

Agricultural research, development and extension activities are aimed at generating objective information that is valuable for agricultural decision makers. It is often difficult, though, to develop recommendations that are widely followed, because of factors that are subjective for individual farmers.

There are both social and economic factors that can impede management change and complicate the development of recommendations. Social factors that are important in management change include the attitudes to the change being considered, farmer age, stage of business development, and general attitudes to agricultural production. Economic issues include the likely level of financial return from an investment in the production input relative to the risk associated with unknown and variable returns from that investment. There needs to be a demonstrated production advantage from the input change, which must also be potentially profitable. But from an economic perspective there is also the question of 'how profitable does it need to be to generate widespread adoption?'

The attitude of research and extension personnel has moved from one of developing 'top down' recommendations for farmers to one of providing more information in helping them make their own decisions. The problem with the 'top down' approach has been the existence of the above factors that are hard to include in the development of relevant recommendations. The challenge when providing information to decision makers is to make that information relevant and valuable.

An approach to developing recommendations for farmers has been to draw on standard production economic theory (Doll and Orazem 1984), consider the likely return to funds invested in new technology and ask the question: 'what is the likely minimum ROI that would be necessary for a technology to be appealing to farmers given that there is variability in likely returns and that they are risk averse?' In a publication by CIMMYT (1988) this approach was considered particularly useful for farmers in developing countries.

An investment in new technology that is likely to return 'on average' $1.50 for every $1 invested provides a likely ROI of 50%. If the likely return is large enough, then it may be considered sufficient to overcome the risk associated with variable returns from that investment. The question then becomes: 'how much of an ROI on a variable input to production is enough?' A farmer contemplating substantial investment in farm development that entails typical agricultural risk might require 10-20 per cent real after tax (15-30 per cent nominal before tax), if an opportunity cost considered to be realistic is around the 10 per cent nominal after tax that can be earned over time in shares, bonds or property. Regarding investments of a capital nature, CIMMYT (1988) proposed that a minimum ROI of twice the cost of capital could be a relevant measure for investments of capital in new technologies. Alternatively, especially for poor farmers in developing countries or for technologies requiring substantial change to a farming system, a minimum target ROI of 100 % (the 2-for-1 rule) was likely to be more relevant.

Generally the decision maker is faced with a reasonably well known marginal production cost (though some of this will be associated with yield) and an unknown marginal revenue which varies according to the marginal output response and price of the marginal output. There is risk associated with the response function and the price per unit of the output. The choice of ROI in additional inputs to production is subjective to the farm decision maker.

If it is possible in an analysis for an advisor or decision-maker to (i) estimate the expected ROI associated with different levels of investment in an input; (ii) incorporate potential variability in returns (due to climatic and other factors); and (iii) include the dependency between variability and ROI; then the analysis may provide useful information to decision makers about investing in more farm inputs to increase profit in any single season and over time. The variable production responses, the associated economic profit responses, and the likely ROIs need to be linked to inform the decision-maker.

Production economic theory

In the approach presented here, use of the constrained profit-maximizing model in conjunction with a full specification of the production response to an added input provides valuable economic information to the decision maker. In this section the production economic theory is presented.

The traditional application of profit-maximizing behaviour can be illustrated for a firm producing an output *y* which is sold at price *p*, and which purchases two inputs x_1 and x_2 at constant unit factor prices w_1 and w_2 respectively (Silberberg 1990). The production process of the firm can be represented by the production function, $y = f(x_1, x_2)$. The objective function of the firm is profits (π), total revenue minus total costs. The assertion of theory is that the firm maximizes the function:

$$\pi = pf(x_1, x_2) - w_1 x_1 - w_2 x_2 . \qquad (1)$$

The first-order (or necessary) conditions for profit-maximization are:

$$\pi_1 = \partial \pi / \partial x_1 = pf_1 - w_1 = 0 \qquad (2)$$

and

$$\pi_2 = \partial \pi / \partial x_2 = pf_2 - w_2 = 0 . \qquad (3)$$

Sufficient conditions for a maximum are:

$$\pi_{11} < 0, \pi_{22} < 0 \text{ and } \pi_{11}\pi_{22} - \pi_{12}^2 > 0 . \qquad (4)$$

The interpretation of the conditions (2) and (3) is that the profit-maximizing firm will employ resources up to the point where the marginal contribution of each factor to producing revenues, the value of the marginal product of each factor (pf_i), is equal to the cost of acquiring additional units of that factor, w_i. These conditions are necessary for a maximum of profit, but the sufficient conditions (4) are also required to hold.

The first-order conditions in complete form are:

$$pf_1(x_1, x_2) - w_1 = 0$$

$$pf_2(x_1, x_2) - w_2 = 0 .$$

These implicit relations in essentially five unknowns (x_1, x_2, w_1, w_2, p) can be solved for the choice functions:

$$x_1 = x_1^*(w_1, w_2, p) \qquad (5)$$

and

$$x_2 = x_2^*(w_1, w_2, p) . \qquad (6)$$

Equations (5) and (6) represent the factor demand curves, and indicate the amount of each factor that will be used as a function of factor prices and product price. In the theoretical model these relations can be used to test the signs of partial derivatives which comprise the comparative statics of the profit-maximizing model (Silberberg). However, if the firm's production functions are actually known then the factor-demand curves can be solved explicitly for the total quantities involved in the model.

Estimating crop responses

The case analysed involves use of a crop simulation model to represent wheat crop responses to a single fertilizer input, N. In the case of wheat there are two crop outcomes, yield and protein, responding to the N crop input with other factors held constant. The example relates to N fertilizer use for wheat production on a Vertosol soil (Isbell 1996) at Gunnedah in northern NSW (Farquharson 2004).

The APSIM model (McCown *et al*. 1996, Probert *et al*. 1998) was used to simulate yield and protein responses as total soil nitrate N levels varied for a range of climate scenarios. APSIM[1] is a cropping systems simulator developed for use as an analytical tool for both research workers and grain growers in the grain cropping regions of Australia. The major factors affecting production addressed by this model are climate variability, soil water characteristics, soil N fertility, variety phenology, planting time and planting density. APSIM is a relatively complex, daily-time-step model capable of simulating soil water and N dynamics in wheat production over relatively long time spans and under crop rotations with either fixed length fallows or opportunistic sowing rules. The model uses historical climate data to simulate growth according to user-defined sowing and management rules.

For this analysis, APSIM was configured to simulate a wheat crop where soil N fertility was reset at each sowing at predetermined levels to generate results according to an experimental design. The APSIM model was run with total nitrate N available to the crop set at levels varying from 25 to 250 kg/ha, to generate crop response functions. Ninety years of daily climatic data were input to APSIM to generate distributions of results for each input level.

Two climate variability issues were accounted for in this analysis, according to the experimental design using APSIM. These were the level of soil moisture (*SM*) at sowing and in-crop rainfall (*ICR*). Soil moisture was included by running APSIM (for each N level) with *SM* reset at typical levels for each 90-year simulation, so that a separate analysis was conducted for each *SM* level. Wheat growers in the northern cropping region of Australia can readily measure the level of *SM* at sowing and this is important information in the crop farming system to determine whether to sow a crop.

For each possible *SM* level, the 90 years of APSIM output provided a distribution of crop outcomes according to *ICR*. The effects of *ICR* were estimated by recording the 10^{th}, 50^{th}, and 90^{th} percentiles (termed 'very poor', 'average' and 'very good' in-crop climate outcomes) of the distribution of crop outcomes (yield and protein content) at harvest. The resulting production responses for one particular level of *SM* are shown in Figure 1.

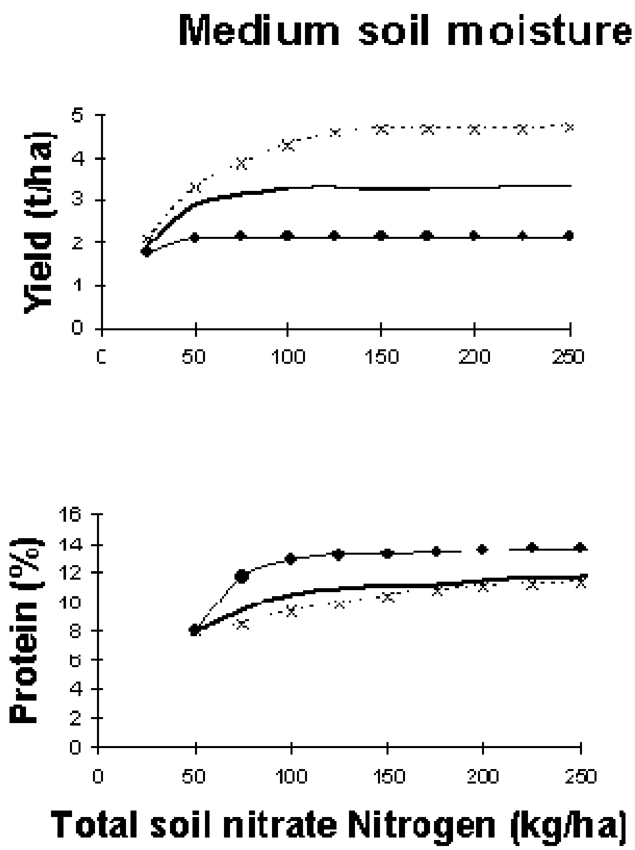

Figure 1. Predicted wheat crop responses to nitrate Nitrogen level, medium soil moisture for a Vertosol soil at Gunnedah (very poor, average and very good in-crop conditions: circles, line and crosses respectively)

In Figure 1 the horizontal axis represents different levels of total soil nitrate N at sowing. A medium *SM* case (124 mm of plant available soil moisture in the top metre of soil) is shown. Yield responses generally rise up to a plateau as N is increased. They also increase, and the onset of the plateau moves to the right, as climatic conditions (*ICR*) improve. In the particular district analysed yield declines, or ‘haying off’, at high levels of N are not generally observed. Protein responses exhibit increasing trends with N, but protein is higher in drier than in wet seasons. For the economic analysis, the APSIM responses were smoothed with a Mitscherlich response function.

Enterprise profit and input demand functions

One way of considering the ‘best’ level of input according to the model objective is to use the profit functions for these N x climatic scenarios. Wheat prices depend on the protein content of the grain, an example is shown in Figure 2. Using these prices and the price of N ($1/kg) profit functions were developed as shown in Figure 3a. The flatness of economic response is quite evident.

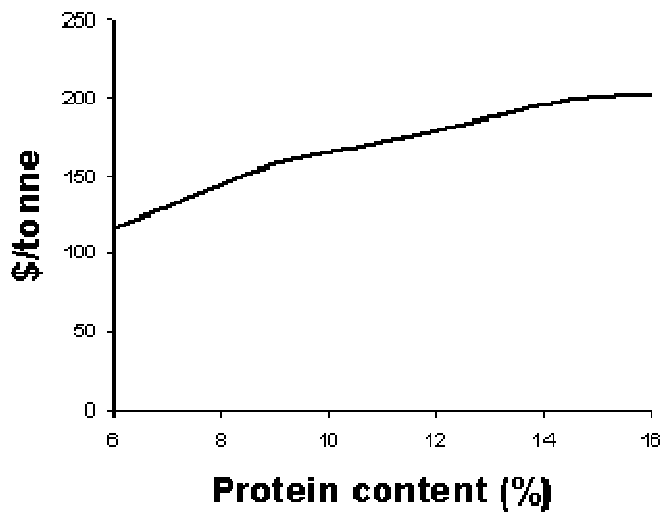

Figure 2. Wheat price according to protein content

However, by considering the marginal conditions of the economic theory above, alternative information can be derived for the decision maker. Using the price schedule in Figure 2, the fertiliser input demand functions (derived from (5) and (6) above) developed based on the response dataset are shown in Figure 3b.

As expected, the demand for N used in wheat production for a particular soil type and location depends on the initial soil moisture, on the existing level of soil N, and on *ICR*. At the time of sowing, when the fertilizer decision is made, the grower can measure soil moisture and soil N level reasonably accurately and cheaply. These input demand functions show what a grower might be willing to pay for an extra unit of N given the expected wheat production responses. The flatness of economic response can be seen in these functions as they change slope near the marginal cost level.

From Figure 3b, the likely returns from investment in N inputs can be assessed. For medium soil moisture at sowing and a measured soil N level of 75 kg/ha, an extra kg/ha of N would earn $2.50, $4.60 and $7.10 for very poor, average and very good in-crop seasons. These are returns to investment of 150%, 360% and 610%, respectively. At lower (higher) levels of measured soil N the rates of return are correspondingly higher (lower).

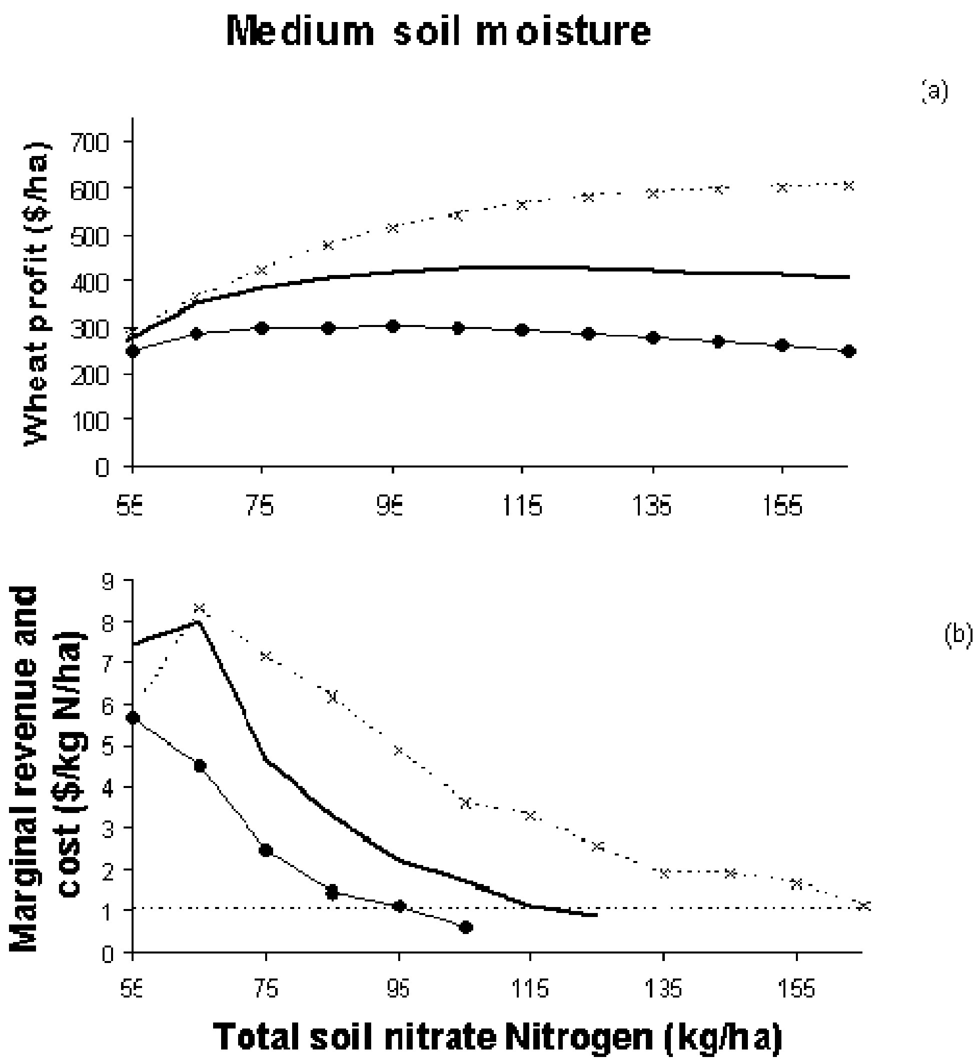

Figure 3. Wheat profit responses and input demand for Nitrogen (profit and marginal revenue for very poor, average and very good in-crop conditions: circles, line and crosses respectively, marginal cost: dotted line)

Decision analysis according to return on investment

In an investment context, wheat growers account for the cost of capital and likely returns when considering input decisions such as N fertiliser for crop production. A grower's degree of risk aversion will depend on these issues, on funds available and alternative uses of those funds, together with their own level of comfort in terms of financial exposure.

From this input demand information a simple decision analysis diagram can be developed which overcomes the flatness of response issue by inclusion of a minimum target ROI. In

Figure 4 the horizontal lines show the cut-offs for marginal ROIs of zero, 100, 200 and 300%. If a grower has measured the soil moisture content (eg medium) and soil nitrate N level (eg 75 kg/ha) at sowing, has an expectation of an in-crop climate outcome (eg average) and has a target rate ROI in mind (eg 100%), then it is easy to determine the ‘best’ target for total soil N level (around 100 kg/ha in this case). The decision then is to consider applying the difference between this ‘best’ level and the measured level in the soil (or 25 kg/ha). If the expectation is for a very good season, the target changes to 135 kg/ha and the application is correspondingly larger. In the absence of further information about *ICR*, growers may use their subjective probabilities about crop prospects to decide on which type of season to fertilise for.

In practice wheat growers often split their fertiliser application between a ‘starter’ amount at sowing and a further application during early crop growth. This strategy can have crop physiological benefits in terms of uptake of N by the wheat plant. In this approach any subsequent fertiliser application is based on better crop prospect information (in terms of prevailing rainfall and temperature conditions) so that the potential gains from specifying fertiliser input demand functions are likely to be more valuable. The probabilities of achieving very poor or very good crop outcomes are refined by this management strategy, which is augmented by simulation model predictions like Figure 1. The expected value of better information can be represented formally via Bayes’ Theorem (Hardaker *et al*. 2004).

Discussion

In contrast to flat profit functions, the input demand functions developed here are steeper and can be used to distinguish decisions according to alternative subjective investment criteria. This analysis is for a particular case of crop, soil and location. The value of an extra unit of N input will depend on existing levels of soil N fertility, on soil moisture at sowing, and on likely crop outcomes due to unknown in-crop climatic conditions. The simulation of bio-physical production responses in conjunction with alternative input and output prices allows input demand functions to be developed for examples of these factors.

Risk-averse farmers will have their own particular situation and their cost of capital to consider when considering financial investments in farm inputs. These issues don’t need to be considered specifically in developing prescriptive decision rules, but can be subsumed into a minimum target ROI chosen by the decision maker. The investment decision will include consideration of likely returns for various crop outcomes. If the decision maker is willing to accept the predictions of a crop simulation model as a basis for action, then the input demand functions for alternative crop outcomes provides information for the fertiliser decisions of individual farmers. If better information becomes available about *ICR* allowing N inputs to be incrementally adjusted, then the value of specifying input demand for alternative outcomes using a simulation model may be enhanced. This approach gives a systematic basis for developing a decision aid that incorporates risky outcomes and decision-maker preferences, without imposing any utility function on the decision maker.

The development of input demand functions for particular districts, crops and soil types can be undertaken by a once-only crop simulation analysis and regular incorporation of updated prices. In a practical farm extension context it is relatively easy to incorporate alternative price schedules to develop fertiliser demand and ROI decision aids like Figure 4.

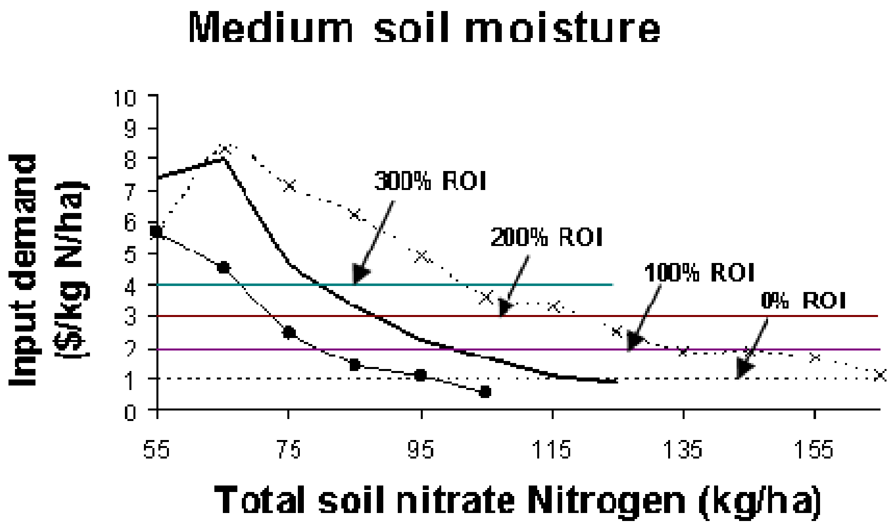

Figure 4. Nitrogen input demand and target return on investment (very poor, average and very good in-crop conditions: circles, lines and crosses respectively)

Conclusion

Given the presence of flat economic responses near the optimal profit-maximising input level, the question addressed here is how to provide better information for crop fertilization decisions. Rather than developing specific recommendations, the approach presented involves presenting information from which decision-makers can make choices depending on their own preferences.

Economic analysis of input demand based on crop simulations of production response can be used to develop objective information for farm decision makers. These analyses are location specific and can provide information on outcomes from alternative scenarios. For fertilizer decisions at particular locations wheat growers can use this information and their own ROI preferences to make decisions that are more than just roughly right.

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[1] Agricultural Production Systems Research Unit URL, http://www.apsim.info/apsim/what-is-apsim.asp