Economic perspectives on nitrogen in farming systems: managing trade-offs between production, risk and the environment

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Abstract
The economics of nitrogen in farming systems are complex, multifaceted, fascinating and sometimes surprising. Economic insights are crucial for making sound decisions about farm-level management of nitrogen, and also about regional or national policy, such as for water pollution. In this paper I present key insights from a large and diverse literature that is often neglected by technical scientists. Issues covered include: the economics of nitrogen as an input to production; nitrogen and economic risk at the farm level; the economics of nitrogen fixation by legumes; the existence of flat payoff functions, which often allow wide flexibility in decisions about nitrogen fertilizer rates; explanations for over application of nitrogen fertilizers by some farmers; and the economics of nitrogen pollution, at both the farm-level and the policy level. Economics helps to explain farmer behaviour, and to design strategies and policies that are more beneficial and more likely to be adopted and successfully implemented.

Key words
Economics, policy, optimisation, profit, risk, pollution

1. Introduction

The global challenge of feeding seven billion people would be impossible without nitrogen fertilizer, but it causes pollution of rivers, lakes and coastal waters around the world, and it contributes to emissions of greenhouse gases. It increases the profitability of individual farmers, but it is over-applied in many cases, wasting money and needlessly worsening environmental problems.

These are economic issues. There is an enormous literature analysing these issues using the tools and frameworks of economics. In this paper I provide a review and synthesis of this large and diverse literature, which is often neglected by technical scientists. Overcoming this neglect is important because the economic insights that will be discussed are crucial for making sound decisions about farm-level management of nitrogen, for understanding farmers' behaviour in relation to nitrogen, for designing regional or national policies for nitrogen-related pollution, and for prioritising nitrogen-related research and extension.

The objective is to identify and describe important economic principles, insights and empirical results, and to illustrate how technical aspects of nitrogen fit into the economic, social and policy world. In this world, the technical issues are important, but they underpin a broader set of perspectives, encompassing profitability, risk, learning, human behaviour, human attitudes, human values, fairness, rights, markets, policy mechanisms, the role of government, and politics.

2. Economics of nitrogen as an input to production

The optimal level of nitrogen fertilizer for a farmer to apply to a crop is case-specific, depending on technical issues (e.g. the type of crop, soil type, rainfall), and socio-economic issues (sale price of grain, purchase price of fertilizer, the objective of the farmer). The simplest economic model addressing this question (Figure 1) is based on an assumption that the objective is to maximise the expected value of profit. The "production function" shows expected yield (i.e. the expected value of yield) as a function of fertilizer rate. This function encompasses all of the relevant technical issues that determine the response of yield to fertilizer. Expected profit is maximised where the slope of the production function equals the fertilizer price divided by the grain sale price (Dillon and Anderson 2012).

The production function for nitrogen fertilizer always exhibits diminishing marginal returns – it flattens out at higher fertilizer rates. In certain situations (e.g. a drought late in the growing season) yield may decline at higher nitrogen rates, in which case the expected yield will probably also decline. It is obvious that if the fertilizer rate is so high that expected yield is decreasing, then the fertilizer rate is too high.

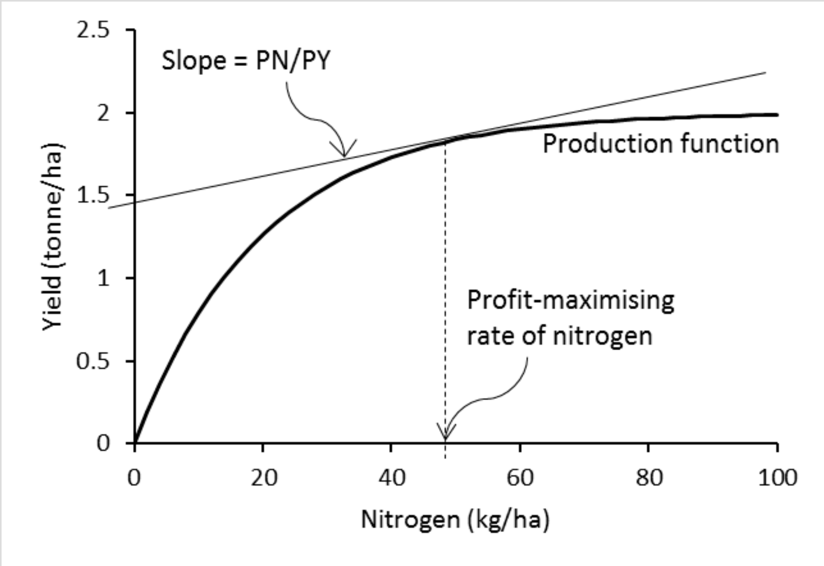

Figure 1. Simple economic model to optimise profit from application of nitrogen fertilizer. PN = price per unit of nitrogen ($/kg), PY = sale price of grain ($/tonne).

Perhaps less obvious is the conclusion that the rate of nitrogen fertilizer that maximises expected profit is less than the rate that maximises expected yield. The gap between those two rates depends on the shape of the production function and the ratio of fertilizer price to grain price. In cases where the production is relatively flat, the gap can be large. Clearly, the optimal fertilizer rate depends not just on technical factors but also on prices. If the price of grain rises or the price of fertilizer falls, the optimal fertilizer rate increases (and vice versa), even in the absence of any change in the technical relationship between fertilizer and yield (Hendricks et al. 2014). Therefore, improving nitrogen use efficiency, if it is pursued by adjusting fertilizer rates, is not necessarily in the best interests of farmers. Grain price (and, to a lesser extent, fertilizer price) also influences the optimal area of a crop. This means that there is a dual effect of rising grain prices on fertilizer use: higher fertilizer rates per hectare, and a larger area of cropping.

3. Nitrogen and economic risk

Maximisation of expected profit is a reasonable approximation of the management objective of some farmers, but many are prepared to trade off some expected profit to reduce risk (Binswanger 1980; Antle 1987). If the riskiness of cropping varies at different rates of nitrogen fertilizer, then this would influence the rate preferred by these "risk averse" farmers. Risk aversion can vary from mild to extreme, depending on the psychological make-up and the circumstances of different farmers. Economists generally measure risk as the variance or standard deviation of the probability distribution of outcomes. The greater the variance of the outcome for a practice (e.g. a fertilizer rate), the less attractive it is to risk-averse farmers.

There are various sources of risk that can affect farmers' decisions about nitrogen fertilizer. One is the price at which the output will be sold. If this price is subject to risk, then increasing crop yield by applying nitrogen fertilizer will increase the farmer's overall risk, by increasing the variance of income from the crop. This means that, for risk-averse farmers, greater output-price risk results in a lower optimal fertilizer rate. Conversely, policies or contracts that reduce output-price risk may increase fertilizer use, depending on what those policies or contracts do to the expected value of output price.

The other main source of risk relevant to nitrogen fertilizer decisions is the riskiness of crop production. The consequence for optimal fertilizer rate of yield risk is less clear-cut than for price risk. It has sometimes been suggested that the application of nitrogen fertilizer reduces farmers' risks, either by reducing their variance of income or by acting as a kind of insurance policy that reduces the probability of bad outcomes (e.g. Sheriff 2005). However, the weight of empirical evidence contradicts this view, both in developing countries (e.g. Mazid and Bailey 1992) and developed countries (Roosen and Hennessy 2003; Rajsic et al. 2009; Monjardino et al. 2015). This implies that policies such as crop insurance are likely to increase optimal nitrogen application rates for risk-averse farmers by substituting for rate-cutting as a risk-reduction strategy.

4. Economics of nitrogen fixation from legumes

The rotation of cereal crops with legumes is an ancient practice that continues to be widely practiced. Legume rotations (or legumes grown in an intercropping system) provide various benefits to cereal producers, potentially including risk reduction through diversification of income sources, reduced cereal crop disease, diversification of weed management strategies, provision of high-quality livestock feed and fixation of atmospheric nitrogen (Pannell 1995). There is much less research on the economics of nitrogen fixation from legumes than there is on the economics of nitrogen fertilizer. There are various studies that have examined the economics of including legumes in farming systems, including nitrogen-related benefits (e.g. Pannell et al. 2014; Preissel et al. 2015) but these generally do not separate out nitrogen from other factors.

Pannell and Falconer (1988) identified two components of the benefits of nitrogen fixation: (a) reduction in the economically optimal rate of nitrogen fertilizer, and (b) contributing to an increase in yield due to biologically fixed nitrogen that does not act as a direct substitute for nitrogen fertilizer, perhaps because it becomes available to crops more slowly as biological material breaks down. The latter is difficult to distinguish from yield boosts due to other factors, such as disease reductions. The existence of these two components means that the value of fixed nitrogen is not equal to the cost of a similar amount of nitrogen fertilizer, because some fixed nitrogen does not actually substitute for nitrogen fertilizer. For the broadacre farming system of south-western Australia, Pannell and Falconer (1988) found that the value of the yield boost due to legumes (including the yield boost due to nitrogen fixation) was far greater than the value of a reduced need for nitrogen fertilizer. They also found that the contribution to profits from legumes in this farming system exceeded the contribution from nitrogen fertilizer.

The economics of nitrogen fixation and legumes more broadly are highly case-specific (Schilizzi and Pannell 2001). Their contributions to profitability can vary greatly between regions and farming systems, and even between different farms in the same region (e.g., Pannell et al. 2014). In some cases, nitrogen fixation is a relatively minor factor in a decision to grow legumes (e.g. where they are grown primarily for livestock feed), whereas in others it is amongst the main reasons.

5. Flat payoff functions

An under-recognised but critically important aspect of the economics of nitrogen is the frequent occurrence of flat payoff functions for nitrogen fertilizer (Pannell 2006). There always exists a range of fertilizer rates that are only slightly less profitable than the profit-maximising rate (i.e. a range where the payoff function is relatively flat), and in most cases, that flat range is wide. For example, Figure 2 shows profit as a function of nitrogen application rate for several soil types in the central wheatbelt of Western Australia. Fertilizer ranges that provide profit within 5% of the optimum are +77% to –51% of the optimal fertilizer rate for sandy loam over clay (i.e., any rate between 24 and 88 kg/ha of N gives almost the same profit). Equivalent ranges for the other soils are +75% to –46% for shallow sandy loam over clay, and +55% to –42% for deep yellow sand. Results broadly similar to this are typical everywhere that nitrogen fertilizer is applied. Jardine (1975) noted that on presenting information to agronomists about flat profit curves for fertilizers, he "observed such reactions as complete disbelief, blank incomprehension, incipient terror, and others less readily categorized". I suspect that little has changed, but the issue deserves a much higher profile.

The management implications of flat payoff functions are profound. They mean that the farmer has flexibility in choosing the fertilizer rate. If a lower rate would better satisfy another objective (e.g. risk reduction), the farmer can choose that rate with little sacrifice of profit. If regulators require a moderate reduction in fertilizer rate below the farmer's economic optimum, the cost to the farmer will be small.

A second implication is that the benefits of precision-agriculture technologies that spatially adjust fertilizer rates within a field will usually be small. Before these technologies were imagined, Anderson (1975) argued that "In pursuing … optimal levels of decision variables, precision is pretence and great accuracy is absurdity". Unless the required rate adjustments within a field are very large, a standard rate is likely to fall within the flat range of the payoff function, meaning that a failure to adjust rates does not result in a large loss of profits. That is why economists evaluating this type of precision technology have found that their benefits are not large. Paz et al. (1999), Babcock and Pautsch (1998) and Thrikawala et al. (1999) all estimated small benefits from variable-fertilizer-rate technology – too small to cover realistic costs of the technology in most cases.

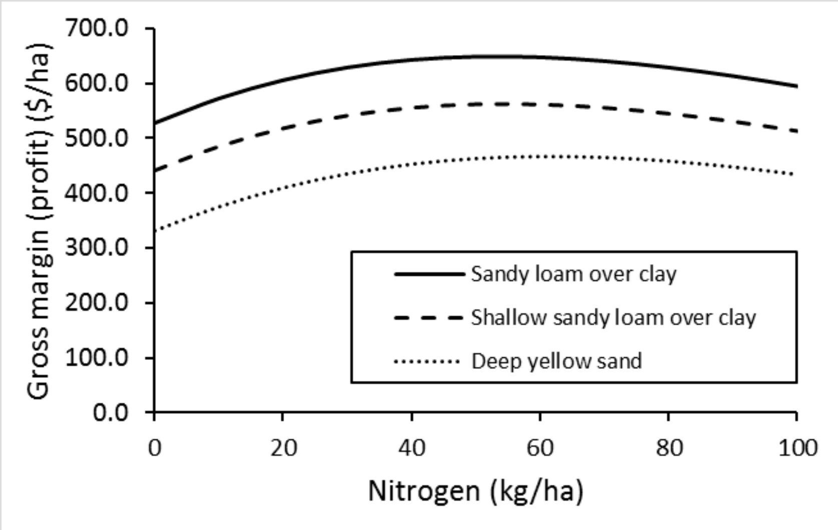

Figure 2. Profit as a function of nitrogen application rate in the central wheatbelt of Western Australia. Production functions, prices and costs from MIDAS model 2015 (Morrison et al. 1986).

A third implication of flat payoff functions is for agronomists developing recommendations for fertilizer rates: they should not recommend a single fertilizer rate for any particular farming context. Much more relevant and helpful to farmers would be to identify the range of rates that will deliver profits within a certain percentage of the maximum (e.g. within 5%). Farmers can then bring in their own preferences when selecting which rate to apply.

6. Over-application of nitrogen fertilizers

It is sometimes observed that a group of farmers is applying nitrogen fertilizer at rates that exceeds local recommended rates. In some cases, the issue is that the rates recommended by agronomists are less than the profit-maximising rates (e.g. Rajsic and Weersink 2008), so farmers are actually in line with profit maximisation. It may be that government programs increase the profit-maximising rate by increasing the expected price of grain (Preckel et al. 2000), and that this is not factored into agronomists' recommendations.

It may also be that farmers are applying nitrogen at rates above their own economic optimum. One likely contributor is the flat-payoff-functions phenomenon, discussed above. Flat payoff functions mean that there is little economic incentive pushing farmers toward the economic optimum. If they are using excessive rates for whatever reason (historical precedent, misinformation), they can continue to do so without sacrificing much profit. Huang et al. (2015) found that in-field training could prompt farmers to reduce their nitrogen rates, suggesting that misinformation was causing over-application. This could include the mistaken view that fertilizers reduce the riskiness of crop production (Sheriff 2005). In some cases farmers apply high nitrogen rates to impress other farmers through production of impressively large and green crops. Over-application in the sense of causing pollution will be discussed next.

7. Nitrogen pollution

Economists recognise water pollution and greenhouse gas emissions associated with nitrogen fertilizer as "external costs". The people who generate these costs (farmers) do not have to bear them, so that they lack the appropriate incentives to prevent or repair the costs. As a result, an external cost can result in "market failure", where the decisions made by unregulated individuals in a free market lead to outcomes that are not in the overall best interests of society. This potentially justifies government intervention of some kind.

7.1 Farm-level economic implications

External costs due to nutrients or greenhouse gases from agriculture arise as a result of activities that are undertaken to generate economic benefits for the farmers. This means that reducing emissions of these pollutants usually comes at a cost. That cost may be borne by farmers (e.g. if they are required by regulation to reduce emissions) or by the broader community (e.g. if farmers are paid to reduce emissions as part of an agri-environmental program). Economists have studied consequences of bringing these external costs into the farmer's production decisions. Studies have identified various potential responses by farmers to the resulting economic incentives, including reductions in fertilizer rates (Nkonya and Featherstone 2000), timing nitrogen applications to better match the nitrogen needs of crops (Huang et al. 1998), switching to organic fertilizer (Vermersch et al. 1993), changing crops (Weersink et al. 1998), switching to break crops requiring little or no nitrogen fertilizer (England 1986), intentional use of wetlands to retain nitrogen (Byström 1998), reduced application of irrigation water (Knapp and Schwabe 2008) and improved management of manure (Andréasson 1990). There have been numerous estimates made of the cost in terms of lost agricultural output as a result of adopting such practices. Typically, the marginal cost of nitrogen emissions abatement is low for low levels of abatement but increases at an increasing rate as the required level of abatement increases (e.g. Helin 2014; Johnson et al. 1991; Doole and Romero 2015). As a result, ambitious targets for abatement can be extremely costly.

Another strand of work examines the impacts on emissions from changes in the farm system or the farming context. The prices of farming outputs have been one focus of study, given that higher prices lead to higher application of nitrogen fertilizer (section 2). For example, Hendricks et al. (2014) examined the impacts of US mandates for use of ethanol in fuel, coming mainly from corn. They found that increases in use of nitrogen fertilizer as a result of this policy would expand the area of the hypoxic zone in the Gulf of Mexico by roughly 30 square miles on average. Another example of a policy which had an unintended consequence for nitrogen pollution was the Gross Revenue Insurance Program in Canada. This increased the relative support for corn, which has higher leachate potential than other crops (Weersink et al. 1998).

7.2 Policy-level economics

The largest body of nitrogen-related economic literature is concerned with government policies for reducing nitrogen pollution. A number of studies have quantified in monetary terms the benefits of policies to reduce nitrogen pollution (Morgan and Owens 2001; Poor et al. 2007) or undertaken Benefit: Cost Analysis of pollution-reduction programs (Hyytiäinen et al. 2015).

There have been many studies evaluating the economic efficiency of particular policy mechanisms to reduce nitrogen pollution, including taxes or levies on fertilizer (Lansink and Peerlings 1997; Bostian et al. 2015), easements (Wu and Tanaka 2005), a deposit-refund system (Hansen 1999), a market to trade permits to pollute (Hanson and McConnell 2008), incentive payments to encourage pollution reductions (Cooper and Keim 1996), quotas on the use of nitrogen fertilizer (Moxey and White 1994) and provision of information to farmers (Fleming et al. 1998). Economists have undertaken studies to select the most effective policy mechanism for reducing nitrogen pollution (Drucker and Latacz-Lohmann 2003) and developed general frameworks for doing that (Pannell 2008). The selection of the most appropriate policy mechanism can make a large difference to the cost-effectiveness of a policy.

There have been economic studies of the interactions between nitrogen pollution and other seemingly unrelated policies. Policies intended to increase farmers' incomes can have the unintended consequence of increasing nitrogen pollution by increasing the incentive to apply fertilizer (Weersink et al. 1998). Conversely, water quality can have implications for the operation of other policies, such as a water market intended to allocate water efficiently to different irrigators (Dabrowski et al. 2009).

There have been many studies to identify efficient strategies for reducing external costs from nitrogen application (e.g., Vatn et al. 1997; Ribaudo et al. 2001; Fröschl et al. 2008), including studies of the optimal spatial allocation of abatement measures within a region or catchment (Doole and Romero 2014; Konrad et al. 2014). On a larger spatial scale, there has been work on the design of systems for internationally coordinated pollution abatement for countries that share an affected water body, such as the countries around the Baltic Sea (Grem 2001; Hasler et al. 2014). Spatial targeting of abatement effort can generate much larger benefits than untargeted policies, although these additional benefits are likely to be offset to some degree by increased costs required to run a targeted program (costs of information and administration).

8. Nitrogen research, development and extension

Economics provides information that can contribute to improved evaluation and prioritisation of agricultural research, development and extension. Alston et al. (1995) provided a framework for integrating information about the benefits and costs of agricultural research to inform decisions about research priorities. There are numerous examples of the framework being applied to actual or potential agricultural research projects, although there are relatively few for research on nitrogen. Related work has investigated the role of new agricultural technologies within the farming system using bio-economic modelling (e.g. Pannell 1995). This provides scientists with insights into the ways in which the technology is likely to be integrated into the farming system, including the scale of adoption within the farm, interactions with other parts of the farming system, and the contribution to farm profits.

Finally economists have contributed to a large literature on the adoption of new practices by farmers. Most of this work aims to quantify adoption and explain past patterns of adoption as influenced by a wide range of economic and non-economic factors (e.g. Pannell et al. 2006), but in recent work Kuehne et al. (2013) have developed a tool to assist scientists and extension agents make predictions about future adoption of new practices. Complementing this tool, Llewellyn et al. (2005) presented a systematic and evidence-based approach to the planning of specific extension messages and the targeting of extension effort.

Conclusion
The insights, evidence and principles outlined here are of central relevance to management, policy and research related to nitrogen. Important results that have been known to economists for decades, such as flat payoff functions, remain unknown to most agronomists and scientists. Accounting for these economic issues has the potential to substantially increase the benefits to farmers and to society as a whole.

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