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Nitrogen for Better or Worse: Issues in Estimating the Benefits and Costs of using Nitrogen Fertilisers[1]

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EXTENDED ABSTRACT/ OVERVIEW

The private benefits of using nitrogen fertiliser for agricultural and horticultural production are large; so too are the social costs from the losses of nitrogen in various forms to the surrounding environment. Emissions from nitrogen fertiliser contribute to global warming and adversely affect air quality and human health and pollute groundwater and surface water. If less of the nitrogen fertilizer used in agricultural and horticultural production went into creating negative externalities for society, and more of it went into creating output with positive private value, further net benefits would result for producers, consumers and society. Nitrogen fertilisers that are less prone to leakage from their agricultural purpose would assist in making this change for the good. Fewer agricultural policies such as subsidies that encourage increased use of nitrogen in agriculture and horticulture and more policy designed to ensure beneficiaries of the use of nitrogen in agriculture and horticulture pay the true social cost the emissions from nitrogen fertilizer are causing, would help too.

The primary purpose of this paper is to review fundamental economic ways of thinking about estimating the private and social benefits and costs of using nitrogen to produce agricultural and horticultural crops. Such a review will identify the types of information required to design and implement policy to promote the socially optimum use of nitrogen fertilisers and to reduce the social costs caused by current farm practices. This review is partitioned into five main parts. Depending on their interests, readers may choose to focus on just one or a few of the parts, rather than the complete document.

In Part 1, *The ARC Research Hub for Innovative Nitrogen Fertilisers and Inhibitors* is introduced. This Hub has the objective of enhancing the efficiency of nitrogen fertilizers in production processes and assessing the prospective improvements that might flow from innovative nitrogen fertilisers with less negative externalities than traditional nitrogen fertilisers. The agricultural economists associated with the project have the task of analysing the social costs of using traditional nitrogen fertilisers and the social benefits and costs that might be achievable with innovative nitrogen fertilizers for agricultural and horticultural production. As is often the case, the project economists and the scientists working together on these

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questions bring different disciplinary expertise and knowledge to bear on the issues. Science and economics have different ways of seeing the issues and the possible solutions. Elements of these differences in approach are introduced in the background section of Part 1. This is followed by a short introduction to the use of nitrogen in agricultural and horticultural production, and a high-level overview of the different methods available to tackle the task of estimating the social costs and benefits of nitrogen use.

In Part 2, a snapshot of some estimates of social costs of using nitrogen fertilizer in agricultural and horticultural production is provided. The conclusion of this part is that a considerable literature exists in which can be found key technical data about pollution from nitrogen used in agriculture that could inform and guide benefit cost analyses of pollution from nitrogen used in agriculture and horticulture in Australia. To answer questions involving economics, empirical technical data needs to be analysed in a framework built on a solid foundation of economic theory, as alluded to in the discussion in Part 1.

This leads to Parts 3 and 4, which outline accepted economic principles and methods of analysis for estimating costs and benefits of activities on the farm, and beyond the farm gate, respectively. The conclusion from Part 3 is that when considering a change to an input to a farm system such as nitrogen applied to crops or pastures, it is necessary to consider the changed response functions and the changed costs of the different inputs, along with associated 'whole system' changes. The concept of the 'rotation-hectare' is introduced. If a crop is grown in a rotation, then the whole of rotation emissions with and without that crop component of the rotation is the relevant measure. Then, even assuming the product quality and price remained unchanged, the new optimum use of the new input has to be estimated to draw conclusions about the implications of the change for the farm system and the wider economy and environment. What else might farmers change? If the price of an input increases or its productivity declines relative to alternative inputs, farmers substitute relatively cheaper or more productive inputs for the relatively more expensive and less productive inputs. A whole-of-system understanding is needed, as well as a clear understanding of the concept of the 'counterfactual'.

In Part 4, the method for a social benefit cost analysis is outlined and discussed. A key point is that a social benefit cost analysis includes all benefits and costs, whether or not they have a market price. The estimate of net social benefit includes all the marginal (or additional) private benefits and costs resulting from the proposed change, as well as all the marginal (or additional) social benefits and costs. This includes social benefits and costs that do not have market values, as often is the case with negative externalities. In the context of applying nitrogen fertilizers, social costs derive from the emissions contributing to global warming and adversely affecting air quality and human health and pollution of groundwater and surface water. Methods for estimating these costs and benefits are set out. The dynamic systems nature of costs and benefits over time is crucial in such analyses, involving concepts of the farm system in which nitrogen fertilizer is used, counterfactuals, discount rates, opportunity costs, time preferences, risk and uncertainty to estimate probable net present values and benefit cost ratios of potential changes to the *status quo* over a planning period. For complicated markets and value chains, system modelling frameworks encompassing science and economics are often required. These methods are also discussed.

In Part 5, the discussion moves to possible policy interventions to assist in reducing the social costs of the mostly negative externalities from nitrogen in their many forms. A range of policy options are set out and discussed, including a direct tax on nitrogen use, a tax on one or more of the agricultural or horticultural outputs derived from the nitrogen application, quantitative restrictions on emissions, permit systems which allow a specified volume of emissions, or subsidies for alternative less pollution-intensive inputs such as enhanced efficiency nitrogen inputs or outputs. Evaluating these policy options involves using the methods outlined in Part 4. A key point is that the incidence of a policy instrument such as a tax is often shared, the final burden being paid ultimately by different parties, not borne where the initial burden is laid. For most agricultural and horticultural products, final demand tends to be own-price inelastic in the medium term, so it is consumers who eventually pay through higher prices for the social cost caused in meeting their needs.

The paper finishes with a brief conclusion and a list of the references cited.

Key words: nitrogen, fertilisers, negative externalities, economics, social benefit cost analysis, social cost

PART 1. INTRODUCTION

Background

In mid-2021 a major research project, *The ARC Research Hub for Innovative Nitrogen Fertilisers and Inhibitors* (https://smartfertiliserhub.org.au/), was initiated at the University of Melbourne, with the objective of addressing environmental and economic challenges created by significant losses of nitrogen (N) fertilisers to the environment. The feasibility and value of innovative N fertilisers with less negative externalities than traditional N fertilisers is the focus of the Hub. Included in the Hub's brief is for the agricultural economists associated with the project to analyse the social costs of using traditional N fertilisers and the social benefits and costs that might be achievable with innovative N inputs to agricultural and horticultural production.

This task led the agricultural economists into the world of scientific research about nitrogen use in agriculture, nitrogen losses from agriculture into the environment, the effects of these losses, and the costs they cause. Some of this work resides in the method category called the 'top down' approach, a world of high-level empiricism, large scale measurement, massive quantities of data and, often, courageous extrapolation. After six months of conversations between the science and economic participants in this project, some disconnections between the science and the economic views of the world are becoming clearer.

For instance, in discussions where the term 'benefit cost analysis' has featured frequently, the agricultural economists and their science colleagues are talking to each other about different things: the scientists commonly think in terms of total benefits and total costs and first-round effects of changes in systems at a point in time, whereas the agricultural economists focus on marginal benefits and marginal costs of changes to systems, as well subsequent effects of any initial change in systems, and over time. Benefit cost analysis is about a change from one state to another over time, and whether the change is beneficial or not, so as to provide information to inform choices about these changes. The right question is not 'what are total benefits and total costs of some current state?', with total benefits then assessed as market price by quantity. The more useful focus is on change in total economic surplus from a *change* in current levels of nitrogen use, and, importantly, how producer and consumer surplus and net economic surplus changes in future with changes in nitrogen use. How does the world look without the form and level of the activity that is contributing to the problem at hand: the difference in the world with and without the activity indicates the contribution of the activity to the problem at hand. That is, the concept of the counterfactual. Adam Smith's 'Paradox of Value' in his *Wealth of Nations*, clarified by Alfred Marshall in his *Principles of Economics,* is also instructive:

> How is it that water, which is so useful that life is impossible without it, has such a low price, while diamonds, which are quite unnecessary, have such a high price? (Samuelson, 1958, p.489).

Scarcity and abundance. Marginal value matters, not total value.

Economists routinely, maybe compulsively, think in terms of the counterfactuals and opportunity cost, the time and dynamics, of 'this compared with that in alternative changing potential futures'. Opportunity cost seems not intuitively obvious to non-economist colleagues prone to looking at 'What is', vaguely implying 'Things would be better if things were different' - but what type of different, how much different, how much better, if at all, over what future time? For example, the contribution an economic activity makes to the cost to society caused by pollution such as nitrous oxide emissions from an agricultural activity can be viewed simply as the total emissions from the activity, and a cost placed on the resulting damage that is caused. Or, from a decision and policy perspective, the question can be asked: 'What would be the cost that society would be suffering from this type of pollution if this particular activity did not take place or did not take place in the way it currently does?' Here the focus is on total social cost 'with' and 'without' the activity, the opportunity cost way of thinking, where if this activity did not take place as it currently does from the resources involved and pollute as it currently does, some other activity or a changed form of the activity in question and the resources used, would take place. *For purposes of policy and decision-making, the contribution to social cost of the polluting activity is the difference between social cost with the form and level of that activity and the social cost that would otherwise exist.*

Once we move from markets to farms, further examples arise of where the scientists and the economists find themselves talking at cross purposes:

- The world does not come to us in straight lines. Diminishing marginal responses prevail. Averages are seldom relevant, marginal responses are the information for decisions and actions.
- Response surfaces are often flat around optima and changes in prices of key inputs may not change input use much.
- The market price of an input is the value that input adds to total value created by using that input.
- Results on farms are the product of the combination of all things: nearly all inputs have substitutes, and there are many ways to achieve goals on farms.
- The necessity of having a sound understanding about the management of farm businesses to assess the likely effectiveness of alternative public policy measures applied at the farm level.

In the rest of this paper, the use of N in agriculture and horticulture is briefly reviewed as are the results of some relevant recent science research. Key economic concepts are introduced that are necessary to answering the question 'In what ways and to what extent will a society benefit from using nitrogen fertiliser more economically efficiently in agricultural and horticultural production?' These economic concepts are also applied. Methods to conduct a benefit cost analysis of a hypothetical new nitrogen fertiliser input that has enhanced technical efficiency are canvassed. Ways of thinking about policy matters and options are introduced.

Using Nitrogen in Agriculture and Horticulture

Farmers all over the world use synthetically made nitrogen to improve yields of crops, pastures, fruit, nuts and vegetables - and a good thing too. The bad thing is that while doing this, they also pollute the environment. Most of the N fertiliser used by farmers is utilised by crops and pastures, but a sizeable proportion of the total N used in farming is lost to the environment via ammonia (NH_3) volatilization, nitrification, denitrification, leaching and runoff (Zhang *et al.*, 2015), adversely affecting the quality of the air and water required by the broader society. These losses of N are known as negative externalities of private production and consumption: in the world of economics, this is a failure of markets to get some things right.

The concentration of nitrous oxide (N_2O) in the atmosphere is 335 parts per billion (ppb) in 2022 (Ritchie et al 2022)), more than 20 per cent above levels in 1750. Around the world emissions of N_2O caused by people contribute 43 per cent of total global emissions and are growing at over 1 per cent per year. The main source of N_2O emissions caused by people comes from farming (Global Nitrogen Report, 2021). These emissions matter because N_2O is a global warming gas, 298 times more powerful at warming than CO_2 over 100 years and it stays in the atmosphere a little over 100 years. N_2O is the third most important greenhouse gas behind carbon dioxide and methane and is responsible for 6.5 per cent of the global warming caused by these three gases. But there is more. Other emissions from nitrogen end up in the natural environment, with ammonium polluting air and causing great costs to human health, and various forms of nitrate polluting water. The difficulties of quantifying these N-related costs in decisions on farms and in policies are important challenges to be overcome if the twin goals of using nitrogen in more economically efficient ways and reducing costs of nitrogen pollution are to be met. Considerable research effort has been devoted to meeting this challenge.

The ARC Research Hub for Innovative Nitrogen Fertilisers and Inhibitors mentioned above has the objective of developing new nitrogen fertilisers to use in agriculture and horticultural production that are more technically efficient, meaning, more of the nitrogen that farmers put on their crops goes to yield and less of it goes to water and air pollution and increasing global warming or is lost to production in other ways. The question of interest is, if nitrogen inputs to agricultural and horticultural production can be made more technically efficient and more of it ends up producing foodstuff, and less of it reducing the quality of air and water, will this be a net benefit to society, how big will the benefit be from doing this, and to whom? And, if this is a good thing to do, how best to do it? That is the focus of this paper.

An Overview of Methods

To answer questions about changing the use of a resource in production, Benefit Cost Analysis in one form or another is required. There are many perspectives on, and ways of trying to answer the question of, how much better off would a society be if more of the components of the nitrogen fertiliser used in the processes of agricultural and horticultural production was turned into output that people wanted and valued, and less was lost to the air, soil and water and made people worse off in important ways?

The theoretical framework for answering the question resides in economic theory. First, there is production economic theory which explains how much of an input the individual farmers who are trying to maximize their profits from farming would use in producing their agricultural output, both under assumed conditions of no risk and certainty and the real-world conditions of risk and uncertainty.

Second, there is neoclassical economic theory about the behaviour of producers and consumers in markets in a competitive economy, with a particular focus on the conditions under which markets work well and the conditions under which markets fail to work. A key focus here is the difference between private optimum levels of use of production inputs in an economy and socially optimum inputs to production when markets fail and negative externalities occur.

Third, there is the body of economic literature in which is embedded Social Benefit Cost Analysis, encompassing the concepts of consumer and producer surplus and total economic surplus or net social benefit, markets and market failure, price and unpriced social benefits and costs, the concepts of time value of benefits and costs, opportunity cost and social rate of time preference, and risk and uncertainty. There is also the use of general and partial models of the operation of the economy or parts of it to simulate the changes in economic surplus that may result from a change in a production process. All of the aforementioned economic theory is required to analyse the impacts of alternative policies that are designed to achieve socially optimum levels of N use in agriculture.

Not all the perspectives brought to bear on the questions relevant here in the massive literature around these topics include economic ways of thinking and understanding. Analyses of these types of questions at times apply perspectives that are (i) predominantly technically-based, (ii) use average relationships between causes and effects, and (iii) owe more to accounting approaches than to economic traditions. Sometimes such approaches are atheoretical; little more than rampant empiricism - the 'get the facts' school of 'research'. While analysis of data that is built on theoretical foundations is an elegantly informative structure, data without theory is a pile of rubble. Empiricism, done properly, measures well 'what is'.

The next question though is 'What relevance is that to what could be? Or, might be?'. And, what is the relevant theory for the analysis. The implicit assumption of empiricism when used without theory to project to policy is that the past is prologue. Most often, it is not. When things change, the best farmers respond too. What sense is there in saying, things have changed, but what I have done in the past will do for me regardless? Sound policy in relation to N fertiliser use is informed by what happens on the farm - if things change on farm, how will farmers change their behaviour? And how will other market participants change their behaviour as a consequence? Everything is connected, change induces change.

PART 2. A SNAPSHOT OF SOME RELEVANT RESEARCH

Globally there is a vast and growing literature about the pollution emanating from the use of N fertilisers. Much of this work is grounded in the science but also, at times, includes sound economic perspectives. As the OECD (2018) explained:

> Since the start of the 20th century, humans have doubled the inputs of reactive nitrogen to the environment (Fowler *et al.*, 2013) and this now poses serious threats to health and the environment (p.1).

The social cost of N pollution is defined best as being the value in monetary terms of the damage caused by losses of N to the environment, discounted to present values, at a particular discount rate. In Europe, the annual total social cost of agricultural N losses arising from damage to human health, ecosystems, and global warming was estimated to be €75-485 billion for the EU27 in 2008 (Van Grinsven *et al*., 2013). In the United States, the total annual health and environmental cost of N pollution was estimated be US$81–441 billion per year in the early 2000s (Keeler *et al.*, 2016).

Sobota *et al.* (2015) investigated N leakage to the air and water in parts of the United States. They found leakages associated with human health, agriculture, ecosystems, and climate ranged from <1 to 125 kgN/ha/year, mostly from N that leaked into freshwater ecosystems. They estimated median annual damage costs (mainly $US in 2008) to range from $1.94 to $2255/ha/year across watersheds, with a median of $252/ha/year (Sobota *et al.*, 2015). In Australia near $1bn has been put into trying to reduce the damage to water quality surrounding the Great Barrier Reef (Gu *et al.*, 2021). China has invested $100bn in a decade trying to improve water quality to acceptable levels (Shu *et al.*, 2022).

Keeler *et al.* (2016) studied the negative externalities associated with reactive nitrogen (N) and estimated the damage costs of N to air, water, and climate. They attempted to account for 'how each form of N causes damages at specific locations as it cascades through the environment' (p.1) in the State of Michigan in the United States. As they describe it, some N is volatised as ammonia, causing local or regional air pollution impacts; some is denitrified to N_2O, contributing to climate change; some is lost to surface water and is transported to oceans where it may be further denitrified along the way or cause hypoxia and eutrophication; and some enters groundwater, potentially affecting drinking water. There is uncertainty over the rates of these transformations; the length of life of different forms of N in each pool; the transport, dilution, and retention processes that affect N as it cascades through systems; and the shape of the damage functions that relate changes in N at a given end point to expected costs (Keeler *et al.*, (2016).

Keeler *et al.* (2016) used the social cost of carbon as a guide to the global warming social cost of N_20, with qualifications about the application of a social cost of carbon. They used the approach for estimating the social cost of non-CO_2 greenhouse gases of Marten and Newbold (2012) who estimated damages from N_2O using the various integrated assessment models to come up with ratios of the social costs of carbon and nitrogen. Keeler *et al.* (2016) estimated the social cost of N_2O at 395 times that of CO_2 and based on the United States government's (then) social cost of carbon of $0.038/kg CO_2 at a 3 per cent discount rate, this gives a social cost of N_2O of $15.01/kg N_2O at a 3 per cent discount rate. The cost of premature death from poor air quality depended on which way the wind blew and location relative to main population centres. This cost was estimated using estimates of the willingness to pay to reduce the risk of mortality of people in the United States. A statistical life in 2006 was valued at $7.4 million. Water quality costs centred on locations of the main aquifers (Keeler *et al.*, 2016)

Keeler *et al.* (2016) noted that many studies have attempted to place a monetary value on damage caused by nitrogen pollution for the European Union, the United States, and China. Limits of these nitrogen accounting studies remain significant, as they say, especially 'their reliance on simplifying assumptions that neither account for the spatial dependencies of N-related damages nor track the transport and transformation of N between the source and those who receive benefits or suffer from damages' (p.1). In their study they attempted to track the movement of a unit of N applied as fertiliser applied in a location. They followed the movement of N fertilizer over space and time, through different reactive forms, to the different costs each form imposes, in different ways and across different segments of the population. Keeler *et al.* (2016) concluded:

> Our results confirm that there is no uniform [social cost of nitrogen] SCN. Instead, changes in N management will result in different N-related costs depending on where N moves and the location, vulnerability, and preferences of populations affected by N. For example, we found that the SCN per kilogram of N fertiliser applied in Minnesota ranges over several orders of magnitude, from less than $0.001/kg N to greater than $10/kg N, illustrating the importance of considering the site, the form of N, and end points of interest rather than assuming a uniform cost for damages. Our approach for estimating the SCN demonstrates the potential of integrated biophysical and economic models to illuminate the costs and benefits of N and inform more strategic and efficient N management (p.1)

Van Grinsven *et al.* (2013) investigated the benefits and costs of nitrogen for Europe. They described their research as a 'critical and comprehensive assessment of costs and benefits of the various flows of N on human health, ecosystems and climate stability in order to identify major options for mitigation' (p.3571). Van Grinsven *et al.* (2013) describe what they did:

> A first estimate of the direct benefit of N-fertilisation (synthetic and organic) for farmers was obtained using N response curves and world market prices of winter wheat, which is the major crop in the EU27, milk and oilseed rape (p.3575)

These authors estimated that 60 per cent of the annual social cost of N of €75−485 in the EU27 in 2008 was related to air pollution which in turn caused 45 per cent of total social cost from adverse effects on human health. Air pollution by nitrogen also generated social benefits by cooling effects of N containing aerosol and also from sequestration of carbon as a result of using nitrogen in agricultural production, benefits totalling €5 billion/yr. These researchers explored internalising environmental costs of N and estimated a 'socially optimum N rate in agriculture' that would lower the optimum annual N-fertilisation rate in North-western Europe by about 50 kg/ha. They too acknowledged the large uncertainties and conceptual issues of their cost-benefit estimates, but concluded the results supported the priority for further reduction of NH3 and NOx[2] emissions from transport and agriculture.

The broad conclusion of Van Grinsven *et al.* (2013) was:

> Our comparison of effects also indicate that N policies should not single out the direct greenhouse effect of nitrous oxide as on the short-term this is a smaller source of damage costs than NOx, NH3 and N-runoff. In the long run toward 2100 the relative share of N2O in total N cost is expected to increase because of the modest potential of reducing N2O emissions from agriculture, long residence time of N2O in the stratosphere and because anticipated future mitigation of air pollution by NOx and NH3 would tend to reduce the short-term cooling effects of Nr. This highlights the need to improve overall nitrogen use efficiency, leading to simultaneous decreases in Nr losses from all sources over time.

Specifically, Van Grinsven *et al.* (2013) mentioned:

> Our estimates of social cost of N-fertilization in EU27 tend to exceed the contribution of N-fertilization to the gross added value of the primary agricultural sector by 70 billion € per year (for the mid values of unit damage costs) (p.3575) …. [but then added] … The potential absence of net social benefits may be due to counting only the benefits that accrue to farmers as revenue from increased yields. In spite of using a low estimate of the benefits from N fertilization, the wide range indicates there is a large scope to increase the welfare gains from N fertilization. The obvious options are reducing emissions of NH3 and NO3 (end-of-pipe measures), as these Nr emissions generate most social costs. Increasing nitrogen use efficiency would reduce N-surpluses and hence all Nr emissions (including start-of-pipe measures) (p.3575).

[2] Note: the meanings of the chemical symbols used are N2 nitrogen gas, N20 nitrous oxide, NH3 ammonia molecule, NH4 ammonium ion, Nr reactive nitrogen, C02 carbon dioxide, C02e carbon dioxide equivalents.

The estimate by Van Grinsven *et al.* (2013), that the social costs of using nitrogen for agriculture exceeds the social benefit, likely comes from, as they say, 'counting only the benefits that accrue to farmers as revenue from increased yields' (p.3575). That is, not using an economic approach and measuring economic surplus to measure total net social benefit but using an accounting approach to valuing the total benefits of agriculture and valuing the increased yields from using N with total output valued at market price. In economics, the market price is the minimum value of the last unit of output supplied. It is only for this last unit of output where consumer willingness to pay, and producer willingness to supply, are equal to the market price. Total net social benefit to consumers and producers is given by consumer surplus and producer surplus.

The demand for agricultural products in any medium or long run will always be less price elastic (more price inelastic) than the supply of agricultural output produced using N fertiliser. If the social cost from N emissions from N used to make agricultural products was greater than the private cost of N use, the ultimate effect of incorporating this social cost into market prices would be that there would still be some consumer surplus from using N to produce agricultural products, albeit with some reduced demand for some of the agricultural product produced using N. As well there would be consumer surplus and increased demand for agricultural product produced without using N, depending on the relative prices of the alternative sources of these agricultural products.

There are also studies investigating all aspects of nitrogen use in agriculture, from production to environmental effects. Several demonstrate that nitrous oxide emissions from nitrogen applications to soil are not linear, as is suggested by models that apply an average emissions per kg of N used. For example, Shcherbaka *et al.* (2014) conducted a global meta-analysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertiliser and found:

> Nitrous oxide (N2O) is a potent greenhouse gas (GHG) that also depletes stratospheric ozone. Nitrogen (N) fertiliser rate is the best single predictor of N_2O emissions from agricultural soils, which are responsible for ∼50% of the total global anthropogenic flux, but it is a relatively imprecise estimator. Accumulating evidence suggests that the emission response to increasing N input is exponential rather than linear, as assumed by Intergovernmental Panel on Climate Change methodologies (p.1).

This finding was supported by Wang *et al.* (2019). Jiang *et al.* (2017) found non-linear responses of ammonia (NH3) to increasing N applications:

> Ammonia (NH3) is an important atmospheric pollutant that threatens ecosystem and human health. Synthetic nitrogen (N) fertiliser applications are a major source of atmospheric NH3. Most of the current bottom-up estimates assume that the NH3 emission response to increasing N application rates is linear, and thus constant emission factors (EFs) are used. However, increasing evidence suggests that NH3 emissions increase exponentially with increasing N inputs. In the present study, we conducted a meta-analysis to generalize the relationship between N inputs and NH3 emissions. Overall, the change in EF per unit of additional N fertiliser input (ΔEF) was positive from 70 experiments with at least three N application rates, suggesting that NH3 emissions in response to increasing N additions grow at a rate higher than linear. Compared to our ΔEF model, the 10% EF model used by the Intergovernmental Panel on Climate Change overestimated NH3 emissions when fertiliser N is applied at low levels, but underestimated NH3 emissions when N is applied in excess. Therefore, our results suggest

> that replacing the constant EF with the N-rate-dependent EF could improve the accuracy of NH3 emission estimate (p.269)

When thinking about policy options to internalise the externalities of nitrogen used for agricultural production, the price elasticity of demand for the N input is key. Breen *et al.* (2012) found farmer demand for N in Ireland was price inelastic, and this was consistent with other such work (Boyle, 1982; Higgins, 1986). They report that Burrell (1989) had concluded that the demand for nitrogen in the United Kingdom was inelastic (in the region of -0.4 to -0.6) with respect to nitrogen price. The magnitude of the price elasticity estimated in the Breen *et al.* (2012) study was -0.39 around the lower end of the range reported by Burrell (1989). This study differed from Burrell (1989) in that it estimated the price elasticity of demand for a single fertiliser type, as opposed to the elasticity of demand for fertilisers in total. The focus of the Breen *et al.* study was on N use on Irish dairy farms where use of nitrogen fertiliser is intensive, similar to Australian dairying. In a US study Williamson (2011) estimated price elasticities of quantity demanded to range from -1.67 to -1.87.

Price inelastic demand for an input means that even with large increases in price, the quantity farmers will use will still be significant, i.e. the percentage change in quantity used changes less than the percentage change in price.

In sum, a considerable literature exists in which can be found key technical data about pollution from nitrogen used in agriculture that would inform and guide benefit cost analyses of nitrogen pollution from nitrogen used in agriculture and horticulture in Australia.

On the positive side however, some initial work has been completed on the potential technical benefits of Enhanced Efficiency Fertilisers (EFF). Lam *et al.* (2022) reported results from a meta-analysis of this work:

> The data show that, relative to conventional fertilizers, NH3 emissions were 50–74% lower (range of the mean reduction) when urease inhibitors were used, whereas N2O emissions were either unaffected or decreased (28–49%). When nitrification inhibitors were used, N2O emissions, N leaching and N runoff decreased by 27–58%, 17–58% and 45%, respectively, but NH3 emissions were unaffected or increased by 13–52%. When formulations combining both urease and nitrification inhibitors were used (double inhibitors), emissions of NH3 and N2O decreased by 36–75% and 30–50%, respectively, whereas N leaching ranged from –51% to +58%. When controlled-release fertilizers were used, NH3 emissions, N2O emissions, N leaching and N runoff decreased by 27–83%, 8–77%, 17–92% and 32%, respectively (p.2).

PART 3. ECONOMIC ANALYSIS AT THE FARM LEVEL

As more of a single variable input is added to production, the rate of increase in yield declines (Figure 1). That is, there are diminishing marginal returns to variable inputs such a nitrogen fertiliser used in farm activities. The maximum yield is never the maximum profit - unless inputs are free. After the maximum yield is reached, additional application of nitrogen results in declining yields.

The economic model that depicts the profit maximizing amount of a variable input to use in agricultural production is shown in Figure 2 (Pannell, 2018). Ignoring risk for the moment, this simply shows that the amount of a variable input to use to maximize profit is the level where the marginal cost of the last unit of the input used just equals the marginal revenue of the extra output that results. This is the level of input where slope of the production function equals the ratio of the price of the input to the price of the output, where marginal revenue (MR) is marginal product by price and price of the input is the marginal cost (MC), and profit maximum is where MR=MC).

As well, the marginal value product of an input to a farm production process is also the firm's demand schedule, also called 'willingness to pay' for that input (Figure 3). It indicates the amount each extra unit of the input adds to the firm's total revenue: the difference between marginal value product of an extra unit of output and marginal cost of an extra unit of input is the extra profit extra unit of input adds to total profit of a firm.

Figure 1. Wheat yield as a function of nitrogen application (note the point of maximum physical yield; this is not the optimal economic yield)

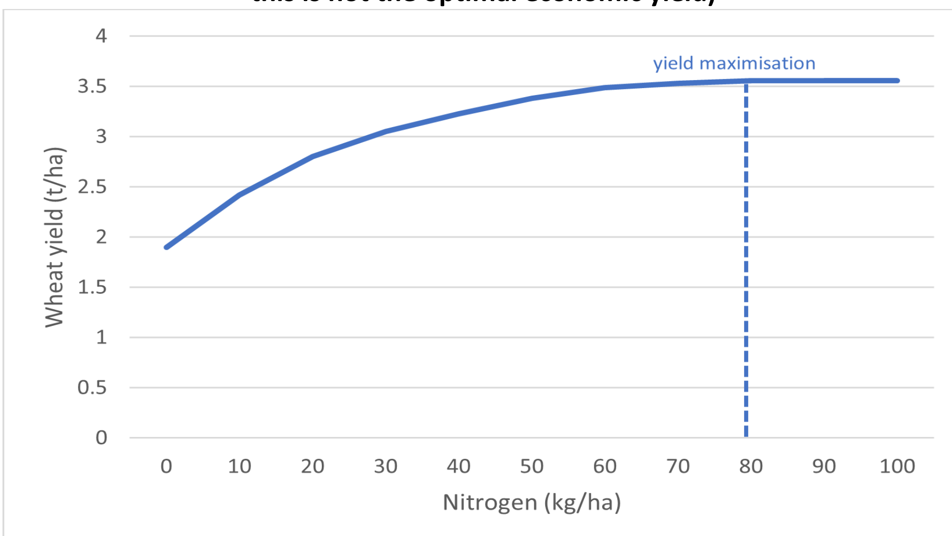
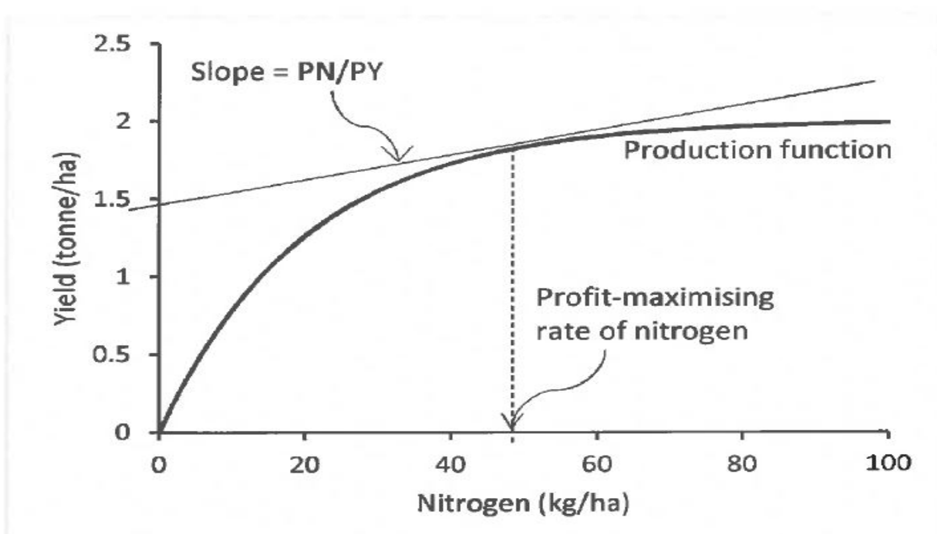


Figure 2. Profit maximising amount of a variable input to use in agricultural production

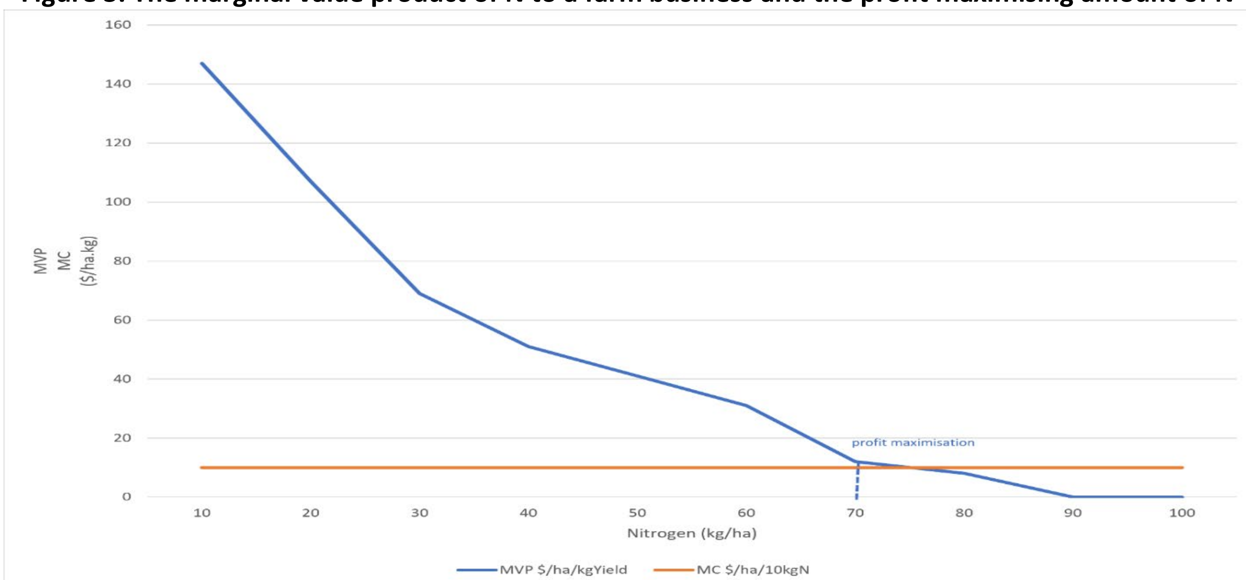


Source: (Pannell, 2018)

Maximum profit, the economic optimum level of a variable input to use in production, such as nitrogen, will be somewhere in the range between where average product is maximized and marginal product becomes zero. The amount of nitrogen that maximizes profit will vary according to the value of the crop and the other inputs, as well as the cost per unit of nitrogen. The firm maximizes profit where the marginal value product from an input just equals the marginal cost of the input.

Response functions around the optimum levels of input use are relatively flat (Pannell, 2006). This means quite a wide range of levels of a variable input will approximate the level that gives the most profit. This has implications for changing level of input use when the costs and returns of an input change, a bit more or a bit less at the margin, has little effect on profit.

Figure 3. The marginal value product of N to a farm business and the profit maximising amount of N



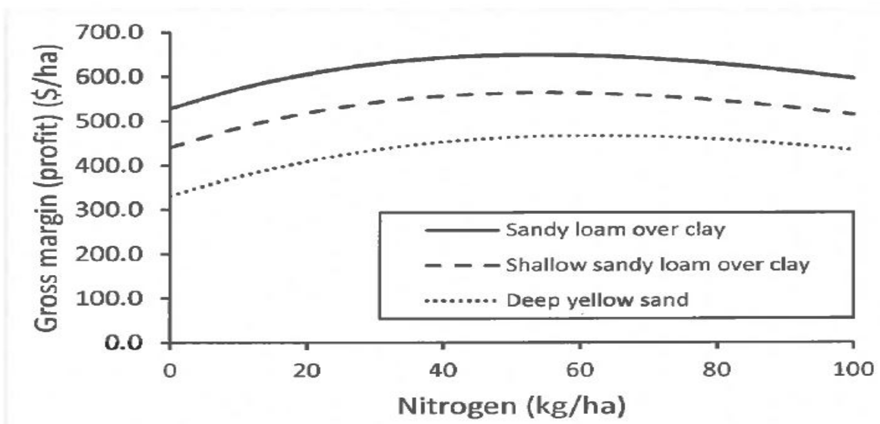
As Pannell (2018) explained:

> There always exists a range of fertiliser 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. An equivalent statement remains true if the farmer's objective includes an allowance for risk aversion; the payoff function (including a negative risk premium) is flat within the vicinity of its highest point.
>
> For example, Figure 2 [our Figure 4] shows profit as a function of nitrogen application rate for several soil types in the central wheatbelt of Western Australia, as represented in the whole-farm bioeconomic model, MIDAS (Morrison *et al.*, 1986; Kingwell and Pannell, 1987). Fertiliser ranges that provide profit within 5% of the optimum are +77% to -51 % of the optimal fertiliser 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 almost everywhere that nitrogen fertiliser is applied. Jardine (1975) noted that on presenting information to agronomists about flat profit curves for fertilisers, 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. (p.3)

The management implications of flat payoff functions are profound. They mean that the farmer has flexibility in choosing the fertiliser 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 a farmer wants to adopt a simple strategy of applying the same nitrogen rate each year, foregoing potentially beneficial adjustments in response to variations in grain price or yield potential, this can be done with little economic sacrifice. If regulators require a moderate reduction in fertiliser rate below the farmer's economic optimum, the cost to the farmer will be small.

Figure 4. Profit as a function of nitrogen application rate in the central wheatbelt of Western Australia. Production functions, prices and costs from MIDAS model 2015



Source: (Morrison *et al.*, 1986, in Pannell, 2018).

Pannell (2018, 2006) also cites evidence that, with risk measured as the variance around the mean, using nitrogen is likely to increase the mean and variance of yield. Using this narrowly focussed view of risk, focussing solely on yield volatility, Pannell suggests that the volatility of yields over time around the mean will be high the more nitrogen is used. Pannell (2018) says:

> The consequence for optimal fertiliser rate of yield risk is less clear-cut than for price risk. It has sometimes been suggested that the application of nitrogen fertiliser 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 (Roosen and Hennessy, 2003; Rajsic *et al.*, 2009; Monjardino *et al.*, 2015). Therefore, risks associated with both production and output price both tend to result in reduced optimal nitrogen application rates. (p.2)

The output and profit and risk of a farm system is the result of the combination of many things. The combinations of risk that create whole of business risk, including both business risk and financial risk, ultimately matters. Farmers mix and match the inputs they use according to the contribution more of an input makes to yield, considering the value they expect for the extra yield and the cost of the extra input. The effect an input may have on yield and price risk of an activity and the extent the risk associated with each activity contributes to whole of business risk, is part of the decision-making challenge. A business with high equity and a diversified mix of activities may be better placed to cope with increased mean and volatility resulting say from using more nitrogen fertilizer in an activity than a business that is in an already precarious risk position. Many farm inputs can be substituted for, other inputs can take their place if they become relatively uneconomic or unacceptably risky, compared to alternative combinations of inputs and the risk that results. Thus most farms can be thought of as multi-input, multi-output production functions with different implications for yield and price risk and how each activity contributes to or lessens whole of business risk. Risk means the calculus of optimal input use becomes more complicated but the principles remain the same.

A firm's demand for an input is the schedule of values of the marginal products of an input as more inputs are used (Figure 3 above). The price of an input in a competitive market is the value of the marginal contribution that input makes to profit, because the rational profit-maximizing producer uses variable inputs at the level where the marginal revenue equals marginal costs - or at least, would do so if the response function and all prices, yields and costs were known with certainty. The answer to the question 'What is nitrogen worth when it is put to production purposes to make possible consumption of the resulting output of the production processes, such as food?' is 'The market price of nitrogen for use as an input to farm production indicates the *minimum value* nitrogen contributes to not only farm profit but also to consumers'. The market price of nitrogen is the minimum value it can have as all preceding units of the input have added more than the market price to the total net social benefits that derive from using the input that resulted in production and consumption of agricultural goods (the sum of producer and consumer surplus which combined make up net social benefit of the input).

The above points are all interesting in the context of the potential role for enhanced efficiency fertilisers that may be used in substitution for traditional nitrogen fertiliser.

For starters, if much of the world does not come to us in straight lines – linear response functions – then thinking about changes in phenomena in terms of average response must always either over- or under-estimate an actual response. And, if the response is of a diminishing nature, as in fertiliser inputs to agricultural production, then in the diminishing returns segment of a whole response function, the average response always overstates the marginal response.

Traditional farm economics advice to farmers about using inputs such as fertiliser is that they will make maximum profit if, under conditions of certainty about the response, the prices of the output and the cost of the input, they used the input up to the point where the last unit of input returns the same as the cost of the last unit of input. Here, profit is at a maximum.

The basis of giving this advice about nitrogen fertiliser is the nature of the response function that is expected to apply on the area of land in question. Experiments will have shown this to be a likely response function of yield to N applied, with other inputs not limiting. Not usually included in the response function prediction is the additional information that while the relation is shown between N applied to the plant and the yield of the plant, some of the N applied will not be used either directly or indirectly to assist the growth of the plant but will instead disappear out of the soil-plant complex altogether, as N leached into subsoil and water or volatilized into the atmosphere. The quantity of losses in this manner will vary across a plot of land with soil type variability, rainfall and soil moisture, timing and nature of N applications, stage of crop and so on. Further, while it is common to claim rules of thumb like 'half the N applied is lost', the quantity of a particular level of N input used for plant growth or lost changes as the quantity of N applied changes. Diminishing returns of yield to input occurs because the plant cannot use as much of the extra

N that is applied and much of the extra N is lost so is not there for the plant to use. These relationships are complex and dynamic. For example, in terms of a response function it may be that of the first 100kg applied to a hectare of crop or pasture, perhaps 75 per cent may go to plant growth and 25 per cent disappear elsewhere; for the second 100 kg/ha the loss may be 50 per cent; while for the third 100 kg N/ha maybe 75 per cent could be lost, unavailable for plant use. The soil, water and plant biology of applied N contributing to yield is complex.

What if the actual N moving out of the soil-plant complex was measured (known) and the 'effective N' required and available at different levels of N was defined. Would this information change the farmer decision about profit maximizing quantity of N to apply? No, because the diminishing contribution to yield of extra N is already accounted for and there is no extra cost involved for the farmer as the increasing amounts of nitrogen is dissipated at no cost to the farmer into waterways and the air.

What might be the case with an enhanced efficiency fertiliser (EEF), less of which is lost to non-plant uses? Is there additional 'not lost' N now available for plants to use? The additional or 'saved' N could be (i) immobilised by soil microbes, which would be available to plants after being decomposed, or stored in more recalcitrant organic matter; (ii) lost to the atmosphere or leached; (iii) used up by plants; or (iv) a combination of the above. The extent these things happen would depend on whether the quantity of N input is reduced when EEF is used. If the N quantity in an EFF is the same as conventional fertilisers, and less N is lost from the EFF, then more N may be retained in the soil-plant system when EEF is used compared with when the traditional N is used. If the N quantity of an EEF is reduced relative to a traditional N fertiliser product, then probably not much of 'saved' N will be available to plants as much of the reduced quantity of N in the EEF should be utilised. In either case, the fate/transport of N varies with edaphic and environmental conditions and plant species. It would be possible to calculate the amounts of N used and lost using a mass balance/N budget and looking at the N input and N output, and/or change in soil N under EEFs versus conventional fertilisers. Or, N isotopes techniques could be used to trace the fate of applied N, looking at how much of the added N would end up in the plant, soil and the environment. In any respect, longer-term data would give a better estimate of the N budget rather than just one season.

According to Mielenz *et al*. (2016) 'N2O emissions measured in Australian grain systems have generally ranged from ,0.1 to 2kgN/Ha/yr.' (p.660). Wallace *et al*. (2016) report losses of N20 'from sowing until harvest of the wheat crop amounted to between 75 and 270 g N2O-N/ha with fertiliser application significantly increasing losses' (p.1). There are some average rules of thumb about N losses from traditional fertilisers, such as N_20 losses may range on average over large quantities of N use in cereal and others crops from 0.1 to 2 per cent of the N fertiliser applied (depending on quantities of N used, how and when it is applied, type of activity and amount and timing of rainfall). As noted above, as a pollutant, N_20 has 298 times the global warming effect of carbon dioxide and an effect of this negative externality is its contribution to global warming.

When considering nitrogen pollution, it should be noted that there are some positive externalities in the form of benefits that may arise from N_20 externalities too. As well, sometimes extra carbon sequestered by plants grown using N is counted as an offsetting benefit. Other times the CO_{2e} associated with making the N too is included in calculations. In the context of market failure and positive and negative externalities, to count soil carbon sequestered in the process of growing crops and pastures and using N to do so, would be wrong on a couple of counts. Soil carbon sequestered is a private benefit that will be captured in yield effects over time from the agronomic benefits of increased soil organic matter, improved soil structure, water holding capacity, availability of minerals and nutrients and so on that result in increased yield. And, if grain or pasture is consumed by animals there is another negative externality created in the form of methane pollution.

Consider the following hypothetical case of nitrous oxide pollution (Table 1), where output produced using nitrogen fertiliser is a stand-alone activity, not part of a rotation of crops for instance, and the nitrogen fertilizer is valued at $600/t and the nitrogen fertiliser cost is $60/100kg. In this case the optimal quantity of N to use is 75kg N fertiliser/ha, where marginal value product from the last unit of output of $20 exceeds marginal cost of the last unit of N input of $15. For the fourth additional 25 kgs of N fertiliser applied/ha, the marginal cost of $15 would exceed the marginal value product of $10.

Table 1. Hypothetical case 1 - Nitrogen output response function

Total N Fertiliser (approx 50% N)	Total Product	Marginal Product	Value of Marginal Product	Marginal Private Cost $0.60/kg N fertiliser
0	1t			
25kg	1.3 t	0.3t	$60	$15
50kg	1.5t	0.2t	$40	$15
75 kg	1.6 t	0. 1t	$20	$15
100 kg	1.65 t	0.05 t	$10	$15

Table 1 includes just private costs and benefits. What if the social cost of nitrous oxide pollution was included and the amount of N lost as N_2O increased as more N is applied? This is shown in Table 2.

Table 2. Social cost of each extra 100kg N/ha

Amount of N fertiliser applied (kg N/ha)	Kg N_2O lost (0.5% for first 2 25kgs N fertiliser,1% of the 3rd 25kgs N fertiliser and 1.5% for the 4th 25kgs N fertiliser)	Cumulative Social Cost of extra 100kg N/Ha
Total 25 kg N fertiliser	0.125kg	$3.75/ha
Total 50kg N fertiliser	0.250kg	$7.50/ha
Total 75 kg N fertiliser	0.5 kg	$15/ha
Total 100 kg N fertiliser	0.875 kg	$26.25/ha

Assume a social cost of carbon of $100/t CO_{2e} which was the cost considered by Stern and Stiglitz (2017) as being the carbon price needed in the near future if the global temperature rise is to be contained to around 1.5 or 2 degrees Celsius and recall that nitrous oxide has a global warming potential of 300 times that of carbon dioxide. Assume also that the emissions identified are the genuine addition to total social cost from the form and size of the activity in question, i.e. the addition to total social cost with the activity minus the addition to total social cost without the activity, from the resources involved.

If the value of marginal product of the nitrogen fertilizer (marginal product by price of product) captured all the benefits of using the nitrogen fertilizer input (no non-economic benefits like an insurance effect from using above this level of N), then, under certainty, the theoretical private optimum amount of nitrogen fertilizer to use would be where the value of the marginal product equals the marginal cost. The social cost at the private optimum of 75kg of N fertiliser input/ha is $15/ha at a social cost of carbon of $100/t CO2e. The third 25 kg of N/ha has a marginal private and social benefit of $20 which is less than the combined private and social cost of $15+$15=$30. At 50kg/ha of N fertiliser used the marginal private and social benefit is $40 and the marginal private cost is $15 and marginal social cost is $7.50, equalling a total private and social marginal cost of $22.50. Using more than 50kg of N/ha but less than 75kg N/ha would be socially optimal as at 75kg N/Ha the additional cost of N and social cost is $15+11.25/Ha =$26.25 and the additional revenue is $25. The same would approach apply to an alternative activity if this activity was to cease and the resources used for some other activity.

There would be other possible social costs too, namely a contribution of ammonia which causes health costs and to water quality which also causes social costs. Including these social costs in the private decision would further alter the socially optimum quantity of N to use.

In this example the added social cost of N changed the profit maximizing decision. The added burden of the social marginal costs of N fertiliser used would be shared between producers and consumers in varying proportions depending on the product being produced and the markets in which it was sold. If mostly exported, the Australian producer would bear the greater proportion of the added cost. If sold domestically the Australian consumer would bear the larger share of the added cost.

A factor worthy of note is that these decisions about using fertiliser are not made under conditions of any such certainty as represented above. Farmers have but a rough idea – evolved over time through trial and error - of what's the best quantity of fertiliser per hectare to use on particular crops and paddocks with particular sets of prices and costs. Indeed, uncertainty and risk about the whole decision, with the knowledge that the shape of the usual response function means that you forego more yield by using too little fertiliser than you will 'over-spend' by using too much fertiliser means there is an inherent tendency for risk averse decision-makers to use too much fertiliser rather than miss out by using too little: a bit more for insurance. For a given degree of risk aversion, adding the social cost of nitrogen pollution to the private marginal cost has the effect of reducing the extent of this 'extra N for insurance'.

Similar ways of thinking about nitrous oxide emissions can be applied when nitrogen is used to grow pasture for feed for ruminant animals. Ruminants excrete on average from 75 to 90 per cent of their nitrogen intake. Suppose a marginal steer was added to a herd, and if this steer was not added, the herd would continue to operate at its current size. The contribution of this extra steer to social cost, the 'with' scenario, is the full amount it adds to social cost, as the 'without' scenario is no change to herd emissions. Suppose this marginal steer consumes enough feed to excrete 0.5kg N_2O per annum, equivalent to 0.15t CO_2e, which at $100/t CO_2e is a social N_2O global warming cost of $15 p.a. This additional cost would be shared between producers and consumers with the share depending on whether the animal is sold for domestic consumption or exported.

Farmers face rising real costs of the inputs they use all the time. What happens on farms as farmers face a rise in their costs in some part of their business? In response to rising real costs farmers substitute higher cost inputs for alternatives and lower profit outputs for alternatives. They adopt new technologies to increase whole farm productivity. They offset a rise in real costs somewhere in their system by expanding or intensifying their farm businesses, to spread the fixed costs of their business over greater quantities of output, i.e. reduce average total cost of production.

Two examples are provided in an Appendix of a farmer weighing up whether to use some Enhanced Efficiency Nitrogen Fertilizer, called New N, in place of the traditional nitrogen they currently use, called Old N.

To summarise, when considering a change to an input to a farm system such as nitrogen applied to crops or pastures, it is necessary to consider the changed response functions and the changed costs of the different inputs. If a crop is grown in a rotation, then the rotation emissions with and without that crop component of the rotation is the relevant measure. Then, even assuming the product quality and price remained unchanged, the new optimum use of the new input has to be estimated to draw conclusions about the implications of the change for the farm system and the wider economy and environment. What else might farmers change? If the price of an input increases or its productivity declines relative to alternative inputs, farmers substitute relatively cheaper or more productive inputs for the relatively more expensive and less productive inputs. A whole-of-system understanding is needed. For example, in dairying or grain growing, substitution of legume plants into pastures and crop rotations are obvious options to substitute for a portion of synthetic nitrogen used if the optimum amounts to use changes.

PART 4. ECONOMIC ANALYSIS BEYOND THE FARM GATE

Every choice has an economic dimension - will the change result in benefits greater than the costs and thus bring a net gain to society? Will the changed situation be in some way(s) better than the situation was without the change? The situation that is relevant is the state of affairs for the community as a whole, not just the benefits and costs of private individuals. This is the fundamental question of all economic analysis and decisions about changes to ways of using resources. The Pareto Optimality concept (Pareto, 1909) holds that provided one person is made better off and no-one worse off, that is an improvement in economic welfare. More practically, if gains are expected to exceed losses and thus potentially the losers can be compensated by the gainers or bribed by the gainers to accept the changed situation, resulting in someone being better off and no one worse off (Kaldor, 1939; Hicks, 1939), then this is a potential Pareto Improvement and this is what social benefit cost analysis (SBCA) attempts to identify.

Benefit cost analysis applies economic theory to choices in a logical way, with rigour, making clear the nature of the choices, costs and benefits involved with particular ways of doing things. In SBCA, net social benefit is the combined effects of the change in producer surplus and the change in consumer surplus. But, even when net benefits cannot all be estimated, SBCA can help in many ways by identifying the nature and sources of the benefits and costs, revealing to the community the high costs of some ways of doing things, estimating the way some beneficial parts of life of some members of society may change when all costs are accounted for.

Implicit in the economic aim of improving people's lot is the notion of economic goals. In many nations and communities, goals include improving economic welfare – which includes improving the quality of the environment and improving social equity. Improvements in economic welfare are often measured as improvements in the net benefits from producing and consuming goods and services, including increasing positive externalities from such activities and reducing the negative externalities.

Questions of equity are not dealt with well with the tenets of the standard economic model operating 'within the existing distribution of income' when net gains to different cohorts of the populations will have greater beneficial effects than for other cohorts. Benefit cost analysis deals mainly with changes in aggregate economic welfare, though affected groups affected by a change for better or worse can be identified, the magnitude of changes in welfare on different people is not able to be compared sensibly, apart maybe from notions about the likely net benefits of reducing defined and generally agreed-on 'disadvantage'. Since Pigou (1920), Bergson (1938) and Samuelson (1954), there has continued a vast literature about the challenges of going from individual utility to social utility using some general welfare function or some such means of adding people's utilities. Indices using weightings is one approach, but the essential subjectivity remains. In practice, if SBCA can identify benefits and costs, value those that can be valued, identify who gains and losers from a change and then inject this information into decision making processes at the levels of political processes and affected producers and consumers, this can at least go some way towards improving situations for the better. Choices have to be made, decisions have to be made – if not in a rational structured way identifying all the benefits and costs and valuing them as best we can, how else? What other method? What other criteria?

So SBCA includes all benefits and costs, whether they have a market price or not. The estimate of net social benefit includes the marginal (or additional) private benefits and costs resulting from the proposal but also includes the marginal (or additional) social benefits and costs (the externalities).

This is a difficult challenge for just a single change at a particular market level of one market. For more complicated questions, modelling approaches are often required. These are addressed later in the paper.

The process of SBCA

Sinden and Thampapillai (1995) set out the steps involved in conducting any social benefit cost analysis:

a) Identify the problem and define the alternatives.
b) Identify the social benefits and costs of each alternative.
c) Value the benefits and costs of each alternative.
d) Tabulate the annual benefits and costs.
e) Calculate the net social benefit of each alternative.
f) Compare alternatives by their net social benefit.
g) Test for the effect of changes in assumptions and data.
h) Make the final recommendation.

Note that in the context of social costs added to by nitrogen-related emissions into the environment, points (a) and (b) above emphasise the with-without approach of comparing alternatives: the relevant concept of addition to social cost of an agricultural activity is the social cost from nitrogen emissions into the environment that would exist with the particular form of the activity minus the social cost from nitrogen emissions into the environment that would exist without that particular form of the activity.

What might a SBCA of an investment to develop a New N product look like? A possible outline is shown in Table 3.

A digression on externalities is relevant here, first, to set out why externalities matter, both for benefit cost analysis and equally for policy. Possible policy responses are covered later in the paper.

A digression on the economics of negative externalities

Figure 5 shows the market for a product that is desired by the community but the production and/or consumption of the product also produces pollution as a by-product that affects third parties to the market transaction and which, under current operating standards, is dumped for free into the natural environment. Also included in Figure 5 is the case where the cost of this pollution is counted.

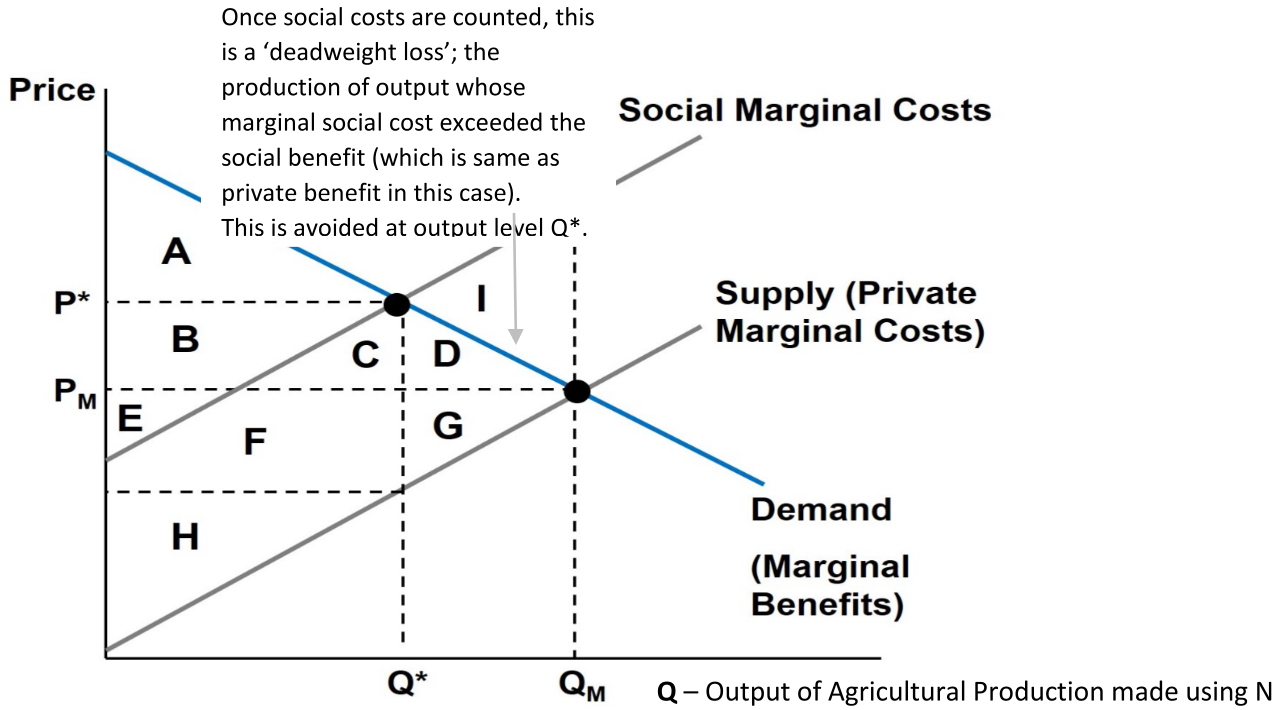
Table 3. A stylised outline of a SBCA

Year	1	2	3	4	5
Benefits					
Primary Benefits Priced					
Increased surplus of producers using New N					
Increased surplus of consumers using products made with New N					
Increased surplus of manufacturers of New N					
Primary Benefits Unpriced					
Reduced pollution costs with the New N compared with pollution costs without the New N					
Secondary Benefits Priced					
Secondary Benefits Unpriced					
Total Benefits (A)					
Primary Costs Priced					
Capital Investment					
Adoption-related costs					
Reduced surplus of producers using Old N					
Reduced surplus of producers using New N					
Reduced surplus of consumers using products made with Old N					
Primary Costs Unpriced					
Secondary Costs Priced					
Secondary Costs Unpriced					
Total Costs (B)					
Net Benefits (C=A-B) Undiscounted					
NET BENEFITS Discounted (Net Present Value)					

The differences in social outcomes are summarised in Table 4. If there is no negative externality, there is no social cost and all costs and benefits are private. Private and social net benefits are the same (Figure 5 and Table 4). The relevant supply and demand curves are the standard private supply and demand curves. The total net benefit is shared between producers and consumers – producer surplus (PS) and consumer surplus (CS). The shares depend on the relative slopes of the supply and demand curves.

Now suppose at the private equilibrium price P_M and quantity Q_M, there is an additional social cost associated with each unit of output Q, in this case a negative externality (pollution) that is constant with each unit of output. This social cost is equal to the areas C+D+F+G+H+I. The Social Marginal Costs curve (Private + External) represents the marginal social cost associated with every extra unit of output, from zero output to Q_m output (Figure 5). The area 'I' in Figure 5 and Table 4 is the social cost of output which was produced when social cost was not counted. Here the private production decision occurred where the value put on the private benefit of an extra unit of output was less than the social cost of an extra unit of output. This is a deadweight loss. Deadweight loss is the amount that society loses by producing a quantity of a good for which the marginal total cost exceeds the marginal total benefit, ie producing too much of a good. The size of the deadweight loss is a measure of the economic efficiency that is lost when the socially optimal quantity of a good or a service is not produced, such as when there is a negative externality.

Figure 5. Welfare analysis of agriculture product market made using N, with externalities



Source: adapted from Harris and Roach (2022)

Table 4. Welfare analysis of two scenarios of the market for an agricultural product made using N (based on Figure 5)

Welfare analysis of a market without an externality, at the market equilibrium Q_m, P_m (Figure 5)	Welfare analysis of a market with an externality at the market equilibrium Q_m (Figure 5)
CS = A+B+C+D	CS = A+B+C+D
PS = E+F+G+H	PS = E+F+G+H
	Externality = C+D+F+G+H+I
Net Benefit = CS + PS Net Benefit= (A+B+C+D)+(E+F+G+H)	Net Benefit = CS + PS – Externality Net Benefit = (A+B+C+D)+(E+F+G+H)-(C+D+F+G+H+I) Net Benefit = A+B+E-I
Net Social Benefit same as Net Private Benefit	Net Social Benefit no longer the same as Net Private Benefit

The social economic surplus/net social benefit at output Q_M is equal to total social benefits minus total social costs. This is equal to (A+B+C+D)+(E+F+G+H)–(C+D+F+G+H+I), or A+B+E-I.

What would we need to know to conduct a social benefit cost analysis change from Old N to New N?

For the farm-level ***without*** case (current situation)

- Typical quantities of N applied annually per hectare to the crops and pastures
- Number of applications in a growing cycle
- Representative production response functions of N applied to crops and pastures over their growing cycle
- Representative prices of N applied
- Representative prices of crops and pasture products produced
- Representative ranges of applications of N and of prices of N and the various outputs.
- Total representative N per year/growing cycle used per some relevant unit of production and analysis: hectare, farm, region, state, national
- Typical amount of N lost annually from production for representative production situations
- Where 'lost' N ends up and all the positive and negative effects of this N lost from production
- The dollar value of these positive and negative effects

For the farm-level ***with*** case (changed 'New N' situation)

- Representative production response functions of New N applied to crops and pastures over their growing cycle
- Representative prices of New N applied
- Representative prices of crops and pasture products produced
- Optimum quantities of New N that could be used depending on adoption rates
- Representative ranges of applications of New N and of prices of New N and the various outputs.
- Total representative New N per year/growing cycle used per some relevant unit of production and analysis: hectare, farm, region, state, national
- Typical amount of New N lost annually from production for representative production situations
- Where 'lost' New N ends up and all the positive and negative externalities of this New N lost from production
- The dollar value of these positive and negative externalities
- If negative externalities of Old N and New N are of the same type, then the difference in quantities of N externalities and their costs can be derived from the quantities of negative externalities from Old N used minus the quantities of negative externalities from New N use, i.e. the net change in negative N externalities arising from the use of New N.

For the rest of value chain case (with New N)

- Change in costs per unit of producing New N compared with Old N
- Change in total costs of N producing firm producing both Old N and New N
- Change in sales quantity and revenue from sales of Old N and New N.

New commercial opportunities that might emerge through the N input and output value chains for EFFs for added net value to be created by participants in the Value Chain. For example:

- Information about industry input and output supply and demand, net gains at farm level, costs of processing, consumer willingness to pay price premiums for specific attributes of products they demand.
- The responsiveness of consumer demand to changes in the supply and price of agricultural products made using N inputs. Change in consumer demand for products identified as being New N/low polluting.

Valuing benefits and costs

Where competitive market prices exist for components of a SBCA, these are the 'true' values to use. The market price of a negative externality such as carbon or nitrogen can be used if the market price truly reflects the social cost. At times market prices for a negative externality such as carbon or nitrogen might represent the outcome of political dealings or interventions that control pollution allowed to be emitted for certain sectors or industries and may not represent a true social cost. A social cost that is considered to be the price needed to achieve a particular outcome can be the right price to use too. For example, if a market price of $100/t of CO_2e was the price required to keep global concentration of CO2e to the level that would contain global warming below 2 degrees Celsius, then this market price of CO2e equals the social cost of the pollutant and is the price to use to value the negative externalities of carbon dioxide emissions. That is, the market price of the pollutant is the social cost of it.

Where items are unpriced, then the true costs and benefits have to be estimated using a variety of techniques in the benefit cost analyst's toolkit. Negative externalities can be valued using estimates of the costs of the damage. Or, rather than estimating the cost caused by the negative externality, the marginal costs of abating the quantity of a negative externality to achieve a given state of affairs can be used to value a reduction in pollution. Hedonic pricing, defensive expenditure, replacement cost of assets, contingency valuation and choice modelling methods including willingness to pay and value of a life are all readily-used techniques to bring to bear on the valuation questions in SBCA.

Stated preference techniques typically involve asking respondents directly about their willingness to pay (WTP) (or accept) a good or service (or for the removal of a good or service) under a hypothetical situation. For example, Veldhuizen *et al.* (2011) conducted a pilot choice experiment in Australia to understand how people trade off the type and amount of a tax or levy they would be willing to pay for specific 2050 emission outcomes expressed in terms of CO_2e concentration levels.

Another approach is to impute WTP from market data (e.g. using vehicle-purchasing decisions to impute WTP for lower fuel consumption). Market-based estimates of damage due to climate change, such as lower agricultural production due to changes in temperatures and rainfall, could be gained using hedonic pricing (Howard, 2014, p.16). However, hedonic pricing requires market data, and these are only available for contemporary or past situations; application to future conditions would require subjective judgement or extrapolation.

Since climate change due to carbon dioxide and related emissions can affect different sectors and have different impacts, integrated assessment models are sometimes used to combine WTP estimates for different impacts to establish the overall impact.

Using Equilibrium Displacement Models to estimate change in economic surplus from a change in a part of the economy

Partial and general equilibrium analysis methods are other ways to estimate the net social benefit of a change in an economy. The 'equilibrium' approaches involve modelling the operation of the economy through the markets from producer to consumer in the whole economy (General Equilibrium) or subsets of the whole economy such as states or regions or individual industries or markets (Partial Equilibrium). Equilibrium Displacement Models (EDMs) of an industry are partial economic models that can be used to track changes in any costs and returns in an industry through the relevant markets to estimate the effects of these changes on economic surplus of the participants in that industry. Generally, the focus of these types of analysis is on private benefits and costs, such as a new technology that changes productivity at the farm level or a change in consumer demand.

For example, Li *et al.* (2019, 2022) used an EDM of the Australian grains industry to estimate the net social benefits of a reduction in grain growing variable costs as a result of a new technology and the effects on economic surplus of an increase in demand for Australian grains. A one per cent reduction in crop rotation variable costs for Australia's Southern Grain Zone was predicted to result in a $18.36 million per year increase in total surplus. All industry groups experienced gains in welfare. The farm production segment was the main beneficiary of the technology shock with an increase in producer surplus of $9.2 million, translating to 49.2 per cent of the total surplus gain. The bulk storage and handling market received $1.60 million or 8.7 per cent of the total benefits. The prices for export grain and grain products were largely unaffected by the technological shock because of their high export demand elasticities, but export quantities increased. The total benefit accruing to all overseas consumers was $4.28 million or 23.3 per cent of the total benefits. A small amount of benefit was captured by other regions due to an increase in grain flows from these regions.

In estimating effects of changes in industries, the markets they sell into make a difference to the size of the benefits and who gets them. Compared to the results for the western region presented in Li *et al.* (2019), the total surplus gain for the southern grains region was noticeably smaller. This was due to a lower gross revenue at farm gate for the southern region grains industry of $2,787 million per year compared to the $3,642 million per year in the case of the western region. In addition, domestic consumers in the southern region gained a much larger share of total benefits at 13.5 per cent compared to the western region (2.4 per cent). This is attributed to the southern region having a greater volume of grains flowing domestically compared to the western region, where the vast majority of gains is directly exported to overseas markets.

An increase in demand for Australian grains had a different set of effects on economic surplus. With a one per cent increase in demand for Australian grains, the estimated increase in economic surplus in the southern region is $16.28 million per year. This is smaller than the results for western region (Li *et al.*, 2019, pp. 83-88) due to the lower gross revenue of export wheat in the southern region of $1,880 million per year compared to the $2,593 million per year in the case of the western region. The majority of benefits are received by the farm sector at $8.96 million or 55.0 per cent of total benefits, due to the high export demand elasticity for wheat. The other major beneficiaries in this scenario include bulk storage ($1.81 million per year; 11.1 per cent of share), overseas wheat consumers ($4.68 million per year; 28.7 per cent of total benefits) and domestic stockfeed users ($1.09 million per year; 6.7 per cent of total benefits). In total, overseas consumers gained 27.5 per cent of the total benefits whereas domestic consumers received 4.3 per cent of total benefits.

Two caveats are worth noting in applying these types of models to issues of externalities, such as N pollution. First, usually the equilibrium modelling methods are static, comparing changes in an economy between two points in time, such as annual performance of an economy or part of it before and after the change. Benefit cost analyses take account of the time involved in making a change and use discounting methods to estimate net benefits in present value terms.

Second, in the analyses cited above, the changes were of a private nature: a change in private farm variable costs, a change in private consumer demand. The changes are represented in the EDM as shifts in demand and supply curves in the markets involving producers, consumers, input suppliers and output processors. The analysis does not include social costs, such as the social cost of nitrogen fertiliser. But conceptually this is possible.

For example, Rohr *et al.* (2020) presented a diagrammatic framework based on value chain failure to show how value chain externalities (social costs) could be modelled, and how the provision of value chain goods could internalise these externalities. The authors noted that work was continuing in this area to extend existing EDMs to account for externalities in a manner that is consistent with the diagrammatic analyses outlined.

Lankoski and Henderson (2017) have gone further and have implemented a range of mechanisms in an EDM framework to capture wedges between private and social supply curves, in the context of how changes in support policies would increase or reduce different types of externalities. Fertiliser use and N related pollution was one of the case studies examined.

PART 5. THINKING ABOUT POLICY

Where the external costs of pollution are not included in market transactions (market failure), this results in too much pollution in the atmosphere and ecosystems. That is, too much of the polluting product is produced and consumed, too much of the polluting technology is used in production processes and pollution costs on third parties are too high. As shown earlier in Figure 5, the social cost of this negative externality is C+D+F+G+H+I. The social cost of the pollutant is the amount people need to be compensated for bearing the cost and not having their welfare reduced by the activities of others in the community. The purpose of trying to estimate the social costs of a polluting input to production, such as nitrogen, is to inform policy-making so that this cost can be reduced.

The choice of the mechanism to correct a market failure depends on the nature of the market failure and the least cost, most effective way of correcting it – and the costs of fixing it including government failure and rent-seeking by private sector operatives. The failure should only be corrected if the costs incurred are less than the benefits of fixing it.

Correcting market failures and improving economic efficiency and generating revenue for government by imposing taxes on the production and consumption of environmental resources was originally proposed by Pigou (1920). As well as environmental taxes, other methods to correct market failures include regulations, tradeable quotas, subsidies and the creation of property rights. The choice of method depends on efficiency, equity implications and administrative cost and effectiveness.

In relation to nitrogen, N pollution causes many types of cost. The benefit of pollution control is a reduction in damages of lives and properties. The geographic extent of the pollution from N matter - some are global, others regional, and whether the effect is a stock or a flow effect. The rate of build up and decay and life of a stock of pollution is important. Whether the source is at a point and is measurable or is non-point pollution that comprises large numbers of small emissions that are hard to measure also matters.

To develop appropriate policy it is necessary to know what price to put on N inputs to agricultural production (whether implicitly via regulation, or quotas or credit schemes, or explicitly via a N tax) to ensure those who experience the social cost from the N use can be compensated by those who gain from the N use (producers, consumers, manufacturers).

Policy development would require information about the aggregated marginal social costs of N use associated with representative farm systems and industries to explore policy options for social costs of N use being included in farm level decisions about N use, and the aggregate and net benefits from policy measures to have beneficiaries of N use in agriculture – producers and consumers and processors – pay the social costs caused by N use in agriculture.

To do this it is necessary to know the size of the various social costs that occur at regional and global scales as a result of different forms of N loss in different types of farm production. Having defined the use of N and private and social costs of N in representative farm systems, possible implications for farm systems of running their systems with the social cost of N losses internalized would need exploring.

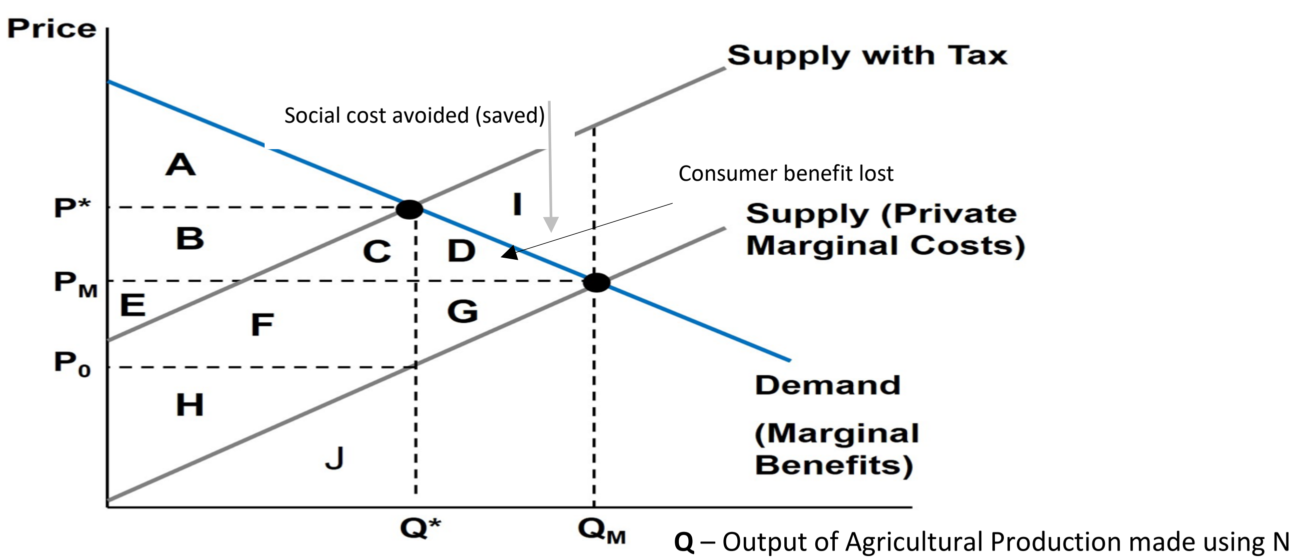
Thinking about policies it is useful to recognize that the costs and benefits of policy that internalizes the externalities are not borne fully where they may first appear; with competition they are distributed through the markets involved and shared amongst participants in these markets, ending up mostly with consumers or producers. The way the burden of costs of externalities and the benefits are shared between consumers and producers depends on slopes of the supply and demand curves for the products affected by the policy.

The case of a tax on an output from using N

The main scope for environmental taxes is as a device to internalize the external costs of pollution associated with production and consumption activities that supply goods that are valued highly by consumers and businesses on forms of pollution that have large and easily recognizable adverse effects and costs. Ease of administration and compliance too are factors.

Figure 6 shows the case where a tax is implemented to increase the price of the output produced from using the polluting input, reducing its consumption and thus reducing the social cost of its use.

Figure 6. Welfare analysis of the market for an agriculture product made using N, with Pigouvian tax on output



Source: adapted from Harris and Roach (2022)

A tax (P^*-P_o)/kg is imposed on the sales of the output to approximate the marginal social cost of the externalities caused by the overuse of N. At price P* only Q* is demanded. A significant proportion of the pre-tax social costs (D+G+I) are avoided. Farmers receive a lower price and consumers are paying a higher price and there is now tax revenue available (B+C+E+F) to compensate the people who are adversely affected by the social cost caused by the negative externality that remains (C+F+H).

A comparison between the market situation with and without the tax is shown in Table 5.

Table 5. Welfare Analysis of two different scenarios of agricultural product market made using N (based on Figures 5 and 6)

Welfare analysis of a market with an externality at the market equilibrium Q_m (Figure 5)	Welfare analysis of a market with a Pigouvian tax that internalises the externality at the social optimum Q* (Figure 6)
CS = A+B+C+D	CS = A
PS = E+F+G+H	PS = Total Revenue - Tax – Production cost PS= (B+C+E+F+H+J) -(B+C+E+F) – J PS = H
Externality = C+D+F+G+H+I	Externality = C+F+H Tax revenue = B+C+E+F
Net Benefit = CS + PS – Externality Net Benefit = (A+B+C+D)+(E+F+G+H)-(C+D+F+G+H+I) Net Benefit = A+B+E-I	Net Benefit = CS+PS+Tax-Externality Net Benefit = A + H + (B+C+E+F)-(C+F+H) Net Benefit =A +B + E
Net Social Benefit no longer the same as Net Private Benefit	A Pigouvian tax, which internalises the externality, increases Net Social Benefit. The negative impacts of too much output of agricultural production made using N have been avoided.

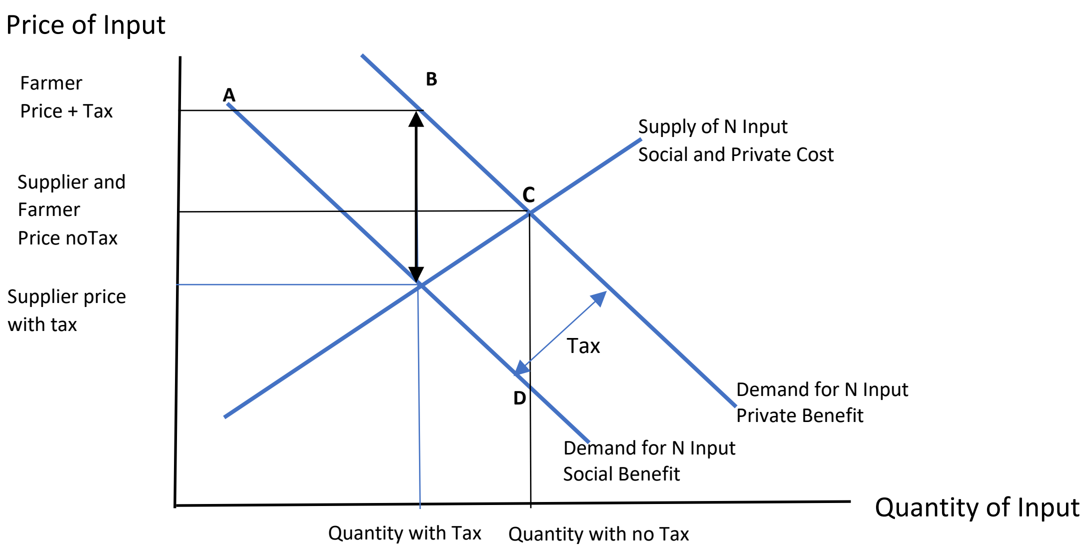
This type of policy is called 'internalising the externality' or 'making the polluter pay' – with the cause of the pollution being both producers who are supplying the product and the consumers who are demanding the product.

Given this framework, let us return to doing a SBCA of an innovation in nitrogen fertiliser that makes it more technically efficient, meaning more of the nitrogen fertiliser applied to an agricultural or horticultural crop or pasture goes to producing crop or pasture than is currently the case and less of any quantity of applied nitrogen fertiliser goes to waste to cause negative externalities. If Governments were able to fully reduce all of the N causing the negative externality with a policy that internalized the externality, in Figure 6 this would reduce the application of N to Q*. On the other hand, if a new product like New N reduced all of the N losses causing the negative externality at no extra private cost to Old N, in Figure 5 this would return the application of N to Q_M. Given the technical information presented above, in practice the outcome would likely be somewhere between these points.

Just as a tax is employed to raise prices and deter consumption of non-preferred products, a subsidy may be used to reduce prices to encourage consumption of preferred products, in a way similar to as shown in Figure 6.

The case of a tax on an input to production

Figure 7. Demand and supply of an input to production, with social cost/social demand included



The potential impact of a direct tax on the polluting input, fertiliser, can also be shown using a price 'wedge' which increases the price of this input and which in turn reduces the quantity of the input demanded. In Figure 7, the supply curve for the fertiliser input from the manufacturers of the fertiliser and the farm sector demand curve for the fertiliser input are shown.

The price wedge simultaneously reduces the price that suppliers of the fertiliser input receive and increases the price that agricultural producers pay. In this case, the cost of the negative externality is directly linked to the use of the fertiliser input as represented by its social derived demand curve (social benefit curve).

In a competitive market situation, without the tax on the negative externality which makes the beneficiaries of the pollution pay, the total cost of the negative externality is given by the area within ABCD. The introduction of the tax on the agricultural input causes the use of the input to decrease and the total cost of the externality to decrease by the area within ABCD.

Marginal externality cost and marginal emissions cost

Another way to represent the situation of a negative externality is to show the quantity of pollution on the horizontal axis. See Figure 8 below and the explanation which draws on Freebairn (2009).

First, some definitions.

Marginal Emissions Cost (MEC): Marginal emissions cost is the additional cost or damage caused by an additional unit of emission. For example, if total damages increase from $50,000 to $90,000 when emissions increase from 100 tonnes per week to 140 tonnes per week, the marginal emissions cost is $1000 per tonne. The marginal externality cost (MEC) typically increases as the quantity of pollution increases; increases in pollution cause increasing damage per unit of pollution.

Marginal Abatement Cost (MAC): The marginal abatement cost (MAC) sets out the additional cost of achieving one more unit decrease in level of emissions. The higher the quantity of emissions being reduced, the greater the marginal abatement cost. On Figure 8 the MAC starts from the 'Business as Usual' position, where to pollute is free resulting in maximum emissions and no abatement. The MAC curve cuts the horizontal axis at Qbau, i.e. the market solution that ignores the externality cost. At the other end of the MAC, the upper limit on abatement costs is the cost of achieving zero emission. As pollution is reduced the costs of reducing pollution further increase. The area below the MAC measures total abatement costs of reducing emissions. Different polluters will have different MAC functions because different technologies of abatement will be brought into action. The aggregate marginal abatement function of an industry is the horizontal summation of the MACs of individual firms.

Efficiency: The MEC represents the marginal benefit of reducing emissions (costs saved), and MAC is the marginal cost of reducing emissions. They are the social marginal benefits and social marginal costs of reducing pollution. The efficient level of emissions (the level that maximizes social net benefits) is where the MEC and the MAC are equal, the point of intersection of MAC and MEC, at Q*.

Moving from the market solution Qbau to the optimum solution Q* involves

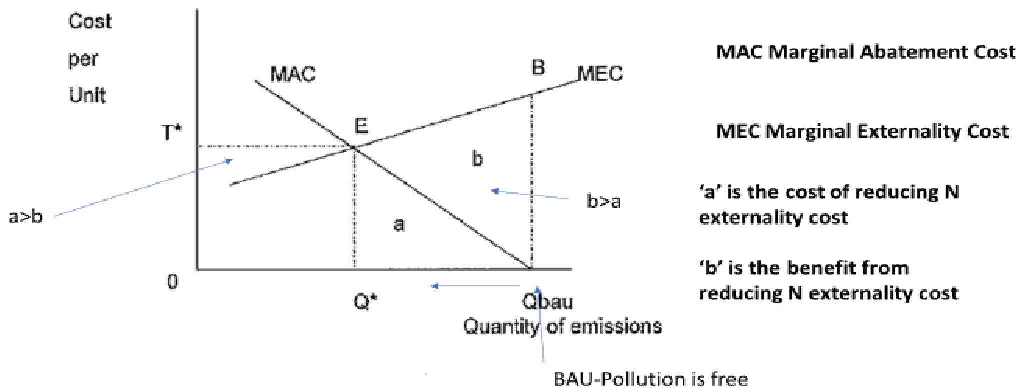
- A cost of area a to producers and consumers of the product that is produced and associated with the pollution
- A benefit in terms of less pollution costs of area a+b.
- A net gain to society of area b. From society's perspective reducing pollution is a positive sum game, and rarely is it optimum to remove all pollution; the last unit of pollution will cost more to remove than any benefit from doing so will provide.

Another way to think about this is that both MEC and MAC are costs. Regardless of what level of emissions a society chooses, it has to incur costs either in bringing down emissions to some level and even then there are costs remaining. At any level of emissions society incurs abatement costs plus costs of damages. The efficient level of emissions is associated with the minimum possible total of abatement costs and emissions costs. The area below the MAC is total abatement costs and the area below the MEC is total emissions costs.

Knowing about the optimum level of pollution requires knowing about the sources and nature of the pollutant, the damage it causes and the costs this damage imposes, the marginal costs of reducing pollution by one unit and the marginal benefits of reducing pollution. And, keeping in mind that these costs and benefits will change over time. Measurement costs are involved. Enforceable in point-source emissions, but difficult to measure actual emissions from nonpoint sources. Non-point sources require a second-best approach of taxing inputs that are associated with emissions, such as taxes on chemical fertilisers, agricultural pesticides.

There will also be costs involved with implementing and enforcing policy actions, when determining the efficient level of pollution. The more emissions polluters are asked to cut back, the more expensive it gets for them to cut back each additional unit of emissions (because of the increasing MAC).

Figure 8. Social optimum level of an externality
(Comparison of Market Vs Social Optimum Nitrogen Externality Cost)



There are various ways of imposing the cost of pollution onto the polluter, on the price axis (as a tax) or on the quantity axis (as a quota or the like). The aim of the policy is that polluters abate their pollution if it is cheaper to abate than to pay the tax, or they pollute and pay the tax if it is more expensive to abate.

To minimize cost, the polluter reduces pollution until their MAC balances with the tax or amount they pay for the right to pollute. The greater the tax, the greater the reduction in emissions. Those polluters who pollute most pay most. If taxes do not affect prices of outputs, and the full tax burden falls on the owners of the firm. If taxes increase prices of outputs, the tax burden partly falls on consumers too. Higher output prices mean lower quantities demanded.

Tradable pollution permits/quotas

A tradeable permit or quota system offers economic incentives similar to emission taxes but works through a market for permits. The authority administering the policy gives or sells permits to polluters. A tradeable permit to pollute entitles the permit holder to emit a specified quantity of a specific pollutant. These permits can be sold and bought in the permit market at a price mutually agreed by the parties. A polluter can:

- put out only the amount of pollution that is covered by the initial holding of permits,
- purchase additional permits from another permit holder and put out more pollution,
- put out less pollution and sell surplus permits to interested buyers.

The choice among these options depends on the cost of abatement and the price of permits. Differences in the MAC between two firms makes it possible for both firms to benefit from trading permits. The price the permit trades for ends up between the MACs of each of the two firms. Trading of permits continues until the MACs of both firms are equal; i.e. no further benefits are possible.

From an industry-wide perspective, a market in permits develops. Like any other good, the demand for permits is downward-sloping. The supply of permits is decided by the administrators of the policy, according to the total amount of pollution defined to be acceptable to meet some objective. Demand and supply give the equilibrium price of permits in the market. Each polluter pollutes to the level where the price of the permit is equal to its MAC. Tradeable permits reducing pollution to the level that is set as the objective and do so at least cost. If the number of permits issued is 'right', the tradeable permit system is efficient.

Tradeable emissions permit and emission taxes are equivalent in that both permits and taxes, set at the right levels, lead to the same level of emissions. Permits and taxes are efficient when the number of permits and the tax rate correspond to the efficient level of emissions. Also, both are equally cost effective for the same targeted level of emissions. Both provide similar incentives to innovation of improved method of pollution control. Incentives are in the forms of saving of abatement costs and payment of lower tax in the emission charges system. Incentives are in the form of saving of abatement costs and revenue from sale of surplus permits in the permit system.

Standard economic views tend towards the view that market solutions such as taxes and tradeable permits reduce the pollution at least cost because individuals know far more about their businesses options to reduce pollution and consumption wishes than command and control measures. They have information not available to governments. With a pollution tax, the private polluters find ways to maximize their reduction in pollution at least cost. Governments gain revenue from a tax on an externality, or from sale of tradeable rights to pollute. If tradeable permits are given to polluters, they gain the benefits.

Compared to emission taxes, enforcement is likely to be less demanding with permits, because it primarily relies on the market.

Typically, taxes can give stronger incentives compared to emission regulations. Taxes lead to new technologies to reduce emissions. Setting appropriate tax rate requires knowledge of MACs as in an emission tax system the tax rate is the marginal abatement cost at the targeted level of emissions. In contrast, a permit system requires no knowledge of the MAC. The number of permits issued is simply the desired level of emissions. The level of emissions is known. The tax set may or may not elicit the desired quantity of pollution as not enough is known about the MACs at the time the tax rate is set – but it is straight-forward to change the tax rate to get closer to the desired level of pollution.

As an example, a study of the economic impacts of non-point pollution from negative externalities from farm management practices in north-east Kansas by Guha *et al.* (2016), whilst focussed mainly on phosphorus, looked at the costs of negative externalities and the possible responses to the traditional policy instrument a Pigouvian tax on the negative externality, as well as the converse, a subsidy when pollution falls below certain levels or land or wetland quality is restored to some standard. They said:

> An aggressive approach to remedy NPS pollution is to institute a system of taxes, known in economic literature as Pigouvian Taxes. These can include input taxes (e.g. on fertiliser) or sophisticated systems based on ambient standards. Ambient standards can be developed and monitored to determine the ecological condition of a river. The observed values can be used to determine whether the public pays a subsidy to farmers when pollution falls below a certain level or charge a tax when the pollution levels rise too high (Shortle *et al.*, 1998). The ambient tax has obvious drawbacks because it can attract free riders: compliant produces sharing the burden of the non-compliant ones. In addition, there can be a significant time lag between the movements of the pollution from the field to the stream. Taxes, in general, appear to be a poor solution to the nutrient pollution problem (Pearce and Koundouri, 2003). Estimates show that a five hundred percent tax

> would cut on farm use by just eight percent (Ag Answers, 1999) and have very little impact on the environment and a devastating impact to the farm economy. (p.3)

The point argued from their analysis is that Pigouvian taxes in this case would not work very well, with a 500 per cent tax cutting on-farm use of P by just 8 per cent. They cite Pearce and Koundouri (2003) about the merits of the tax solution. These author's preferred solution was for changing farm management practices to reduce negative externalities it was better to use subsidy-incentive based schemes. The main point is that situations and policies have to be analysed and problems resolved for their individual circumstances; 'in principle' is but the start to devising prescriptions.

Further policy options

Other options are regulations to restrict pollution emissions via controls on the emissions themselves, on production processes, or on the quantities of the desired quantities that can be produced, all with the aim of restricting pollution to the optimal level. These too raise the cost of polluting and help move the marginal social cost nearer to the social optimum. With regulations, economic surplus goes to some of the regulated parties. The information costs and difficulties of command and control measures are high. Once a regulated quantity of pollution reduction is reached, there are no incentives to go further (unless regulations are tightened), whereas a tax provides a continuing incentive to reduce pollution or find alternative ways to produce the product that are less polluting.

Another option is the creation of a property right to pollute, with the property right able to be allocated to the polluter or the third party who is affected. This is the Coase solution. The large number of people involved and associated high transactions costs usually rules out this option.

A bond payment that is made up-front and refunded if the pollution that happens is less than some defined desired level is a third option.

Finally, subsidies can be provided for substitute products and production processes which are less pollution intensive than the methods currently used by operators in the market. Such subsidies reduce the MAC. Combinations of the private tax stick and the public subsidy carrot can be effective. Some public policies exacerbate pollution, such as subsidies on an input that causes pollution.

It should be borne in mind that cost effectiveness is a different concept to efficiency. Cost effectiveness is about achieving a given target at the minimum possible cost, whereas efficiency is more than cost effectiveness. Efficiency involves both marginal benefit and marginal cost. With cost effectiveness approaches the benefit of achieving the set target is the same; what matters is the cost of achieving it. The focus is on how to minimize the cost of reducing pollution. The objective of cost effectiveness is to choose the alternative that achieves the given target at the minimum cost possible.

In sum

The question of who bears the final cost of these interventions is interesting. A portion of all the extra private costs of supply is passed on to consumers as higher prices at a reduced quantity of output. The more elastic the supply of the final product relative to the demand, the greater the share of the extra costs associated with the policy intervention is passed forward in the form of higher prices. If supply is perfectly elastic (as in a constant-returns technology), all of the cost of the externality is passed onto buyers of the product. It is common to see with indirect taxes that most of cost of an indirect tax, like a tax on pollution, is paid by consumers.

First-best is still probably a pollution tax, but because of administrative and compliance costs, second best may be practical. Second best is a mix of policy interventions that are complementary. Policy makers also need to be aware of unintended consequences, even on the environment. Key is to adhere as much as possible to the polluter pays principle where the cause of the problem pays a sum equal to the marginal external cost on the most direct measure of the pollutant that is causing the external costs on third parties. This approach internalizes social costs while providing incentives and rewards for more efficient production, consumption and investment decisions. Most internalized costs will be passed forward to consumers, and government collects revenue from the tax that internalizes the external cost.

Reduce and cease policies that make things worse

The 'in-principle' argument that agricultural policies that subsidize the returns from agricultural outputs or subsidize the cost of agricultural inputs will encourage the use of nitrogen beyond the private competitive market optimum, let alone the social optimum, has been demonstrated to be correct in research by the OECD (2017). Researchers used farm-level and market-level analytical approaches (equilibrium displacement modelling) to investigate effects of 'policy instruments on input use and land use and associated effects on greenhouse gas emissions, water quality, and biodiversity' (OECD, 2017, p.4), investigating the effects of policy-related changes in key production inputs that are linked to environmental impacts, including fertiliser, agricultural chemicals (e.g. pesticides), and cattle numbers.

The point is that excessive use of nitrogen can result from (i) the obvious increasing use of nitrogen because it is made cheaper by policies than would be the case without the subsidy and (ii) the more subtle 'second-round' effects where distortionary policies result in expansion of farm activities that also use nitrogen.

The OECD farm-level analysis showed that market price support and payments based on variable input use (nitrogen fertiliser) resulted in the highest level of nutrient runoff and net-GHG emissions, and also had negative impacts on biodiversity. Other policies had other distorting effects such as causing farm activities to change and land allocations to different activities to change. Policies not linked to activities and inputs-called decoupled- were environmentally neutral in effect, if farmers were neutral in their attitude to risk. Risk averse farmers though responded by increasing use of risk-increasing inputs: nitrogen was considered to be such an input as using it increases variance (as well as the mean) of crop yields and 'thus decoupled crop area payments were found to increase fertiliser use and its associated environmental impacts' (OECD, 2017, p. 4). For an exporting country, where the extra production resulting from the distortionary policies are sold at same price, the effects of policies such as an input subsidy and price support are not competitive with but complement each other, i.e. all the extra production is disposed of overseas.

Conclusion

This paper has been a slow, oft side-tracked, meander through economic theory and application, traversing ground well-trodden, going from paddock to policy. The aim of this attempt is to gather in one place as many of the relevant extant concepts necessary to think and talk sense about the social cost of using N to grow the grass, grain, fruit and vegetables that people demand.

The social cost of using N can be high and will depend in complex ways on the mix of soil type, weather patterns, crops grown and livestock fed, as well as the attitudes and preferences of agricultural producers, agribusiness partners and food and agricultural product consumers. But there are well established theories available to both estimate these costs in particular situations and to predict the effectiveness of particular policy proposals aimed to reduce these costs. Optimistically, new technologies can assist as well. As reported by Lam *et al.* (2022), research results to date indicate that the potential percentage losses of N prevented by Enhanced Efficiency Fertilisers range from 20 to 50 per cent and more for the main types of N losses.

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Appendix. Farm Case Studies

Here are two examples of a farmer weighing up whether to use some EFF nitrogen fertiliser, called New N, in place of the traditional nitrogen they currently use, called Old N. For an initial simple example, imagine that Old N fertiliser does not have the social cost it causes included in its cost. And assume the yield-input response function for Old N and New N are the same, though New N costs more than Old N.

Case study 1: a dairy farm

The N-Dairy Advisor tool (Stott *et al.*, 2018) is used to estimate the optimum Old N to apply to a typical mixed species, predominantly ryegrass pasture in Gippsland in Spring, for a given grazing management strategy and values of extra pasture DM consumed and cost of N fertiliser. The N-Dairy advisor uses a Nitrogen-Pasture response function derived from over 2000 nitrogen response experiments across Australia. A generalized response curve was derived as well as nitrogen response curves specific to regions and seasons. The general nitrogen pasture response model is represented mathematically as follows:

$Y= \alpha (1- e{-}\beta{-}\lambda N)+ \varepsilon$

where Y is pasture yield scaled as a proportion of the maximum obtainable yield, N is nitrogen applied (kg N/ha), α, β and λ are coefficients, and ε is error. The coefficient α is the maximum attainable pasture yield at non-limiting N set to 1, β is an implicit measure of existing soil N that varies with Australian state and season (like in Table 1), and λ is the curvature coefficient. In the generalized response function, the value of λ is 0.026 for all state and season combinations.

This example is of a hypothetical 180ha dairy farm in Gippsland, milking 330 cows and using rotational grazing. The analysis is for adding N to pastures and grazing them in the Spring rotations. Cows are removed from paddocks when 1500kg of pasture dry matter remains and the cows are re-introduced when 2500 kg of DM is available. Pasture DM in Spring is worth $150/tonne consumed and Old N costs $1000/t. The optimum quantity of Old N to apply is 37kg N/ha for each rotation. This is for a hypothetical case of operating under conditions of certainty and the farmer wishes to use N inputs up to the level where the marginal revenue (marginal value product) to marginal cost ratio gives a return on marginal capital of 1% on the last unit of N applied, i.e. close to the profit maximizing rule MR=MC.

If the same response function as Old N applied for a New N product that reduced some of the loss of N into water and air that occurs with Old N, and if none of this reduced loss of N was available to produce DM, and if the only difference was the cost of the New N at say $1500/t, (i.e. 50 per cent more expensive/t than Old N) the optimum quantity of New N to use would be 21kg/ha/rotation. i.e. 10kg/ha less of new N than old N.

However, because the response function is flat around the optimum, the reduction in DM produced with the lower amount of N used is not great, declining from 997kg/ha to 865 kg/ha. At $150/t for Spring DM, the loss of income for the farm is $10,692. The farm fertiliser cost changes from $19,980 cost for Old N to $17,010 cost for New N (less New N at higher price/kg). The net effect of saved fertiliser cost and reduced DM (income) produced is that the farmer is worse off by $7,722 by changing to the higher private cost/ lower social cost New N – if there is no extra DM production that results from the New N that is applied and losses from which are reduced compared with Old N.

If an EEF New N reduced losses of N and if enough of this was available to plants to produce an increase in pasture consumed - in effect New N having a response function that supplies more N and produces more DM yield at each level of N use – then the dairy farmer using the New N could make as much profit as they did when they were using the Old N. In this case, to cover the $7,722 increase in cost from using the higher cost New N, if the New N delivered 50t more DM at $150/t across the whole farm, or around 300kg/DM/Ha (if the farm had 10t DM consumed/Ha with Old N, then 0.03 per cent more DM production than Old N), the farmer maintains the same profit as they did from using the Old N. The winner is the environment that experiences less N leakage.

Case study 2: a wheat farm

Consider another case, wheat growing. Again, a Mitscherlich production response function is used. Again, both Old and New N products deliver the same yield response. Wheat is worth $200/t and Old N fertiliser costs $600/t. The farmer is growing 1000ha of wheat. Again, there is certainty and the farmer is using N up to where MR virtually equals MC, with 1 per cent return on the last unit of N applied. With the yield function that is considered to apply across the farm and using Old N, the optimum N application is 200 kg Old N/ha, giving a yield of 4.7t/ha. New N has the same response function but costs more, at $800/t. The profit maximizing level of New N is 175kg/ha, with a yield of 4.63t/ha. The production function is flat around the optimum.

With Old N, total N cost for the farm is 200kg Old N/ha*$600/t=$120,000. With new N total farm N cost is $140,000. If the same production function applied to both N fertilisers, with new N there is less yield and income and higher cost, less gross margin, less farm profit with the New N. Less yield with New N would also mean some yield-related variable costs, like harvest, insurance, levies, would also be less. The question arises: 'If some of the N that is not lost into the air and water with New N was available to produce extra grain, how much extra grain would be needed to be produced for the farmer to be as well off as they were using the Old N?' An extra 100 tonne of grain income at $200/t would be needed to equal the extra $20,000 cost of the new N, which would be an extra 100kg/ha which is about 2 per cent of the optimum yield of new N without counting benefits from N that previously lost becoming extra yield. In this case the answer is around 2 per cent extra grain would be needed from the New N compared with the Old N, for farm profit to be maintained. Would this be possible if the New N reduced losses of N of 20-30 per cent compared with losses from Old N? Or, what alternative combinations of activities, inputs and outputs would now be more profitable than growing this crop using New N?