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Using Nitrogen Fertilizer to Grow Irrigated Cotton in Australia: Marginal Benefits and Costs of Nitrogen and Nitrous Oxide Emissions[1]

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Abstract

The nitrogen (N) fertilizer used to help grow fully irrigated cotton in Australia adds, through several pathways, nitrous oxide (N_2O) to the stock of nitrous oxide in the atmosphere and increases the global externality cost of the warming climate. The focus of this analysis is on the extra social benefits and the extra private costs and negative externality costs of using different quantities of N on land in NSW and QLD to grow cotton over a year, and over the coming 15 years, as compared with not growing cotton on that land and replacing the activity with another economic activity. Starting at the farm, a welfare economics framework including the concepts of response of crop yield to N fertiliser, private costs, externality costs, marginality, with-without counterfactuals, opportunity costs, crop rotations, discounting, probabilities, consumer surplus, producer surplus and net social benefit are used to estimate the size of the social benefits and costs of N used to grow irrigated cotton. In the case analysed, with an illustrative counterfactual, the externality cost of direct N_2O emissions from growing cotton after counting for the counterfactual was $102/ha yielding a Benefit to Cost (B:C) ratio of 7.2:1. The net social benefit on the industry over 15 years at a 5 per cent real discount rate per annum in net present value terms was $5.6 billion with an annuity of $541 million. In the case analysed and with the probabilities assumed for the values that the key uncertain variables could take, with only direct N_2O emissions counted as the negative externality of the N used, there would be a 90 per cent probability that the B:C ratio of N used to grow cotton was between 5.4:1 and 9.6:1. There would be 55 per cent chance the B:C ratio would be more than 7:1. There would be zero chance the B:C ratio would be under 4:1. A significant finding about the negative externality of the N_2O emissions from the N applied to cotton was that $80 of the $116/ha externality cost from the N_2O emissions came from the marginal 50 kg of N/ha that was used. If the response function is relatively flat around the typical level of N/ha that is used in a typical year, then the marginal units of N applied would be adding little extra cotton yield *relative* to the extra externality cost attributable to the N_2O emissions. In this situation, there would be scope for small reductions in N/ha used to grow extra cotton to bring large reductions in the externality cost of the N_2O emissions from N used to grow cotton.

Keywords: nitrogen fertiliser, cotton, nitrous oxide, externality cost, marginal benefits and costs

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Introduction

Nitrous oxide (N_2O) is a polluting greenhouse gas with a global warming potential over 100 years that is approximately 300 times greater than that of carbon dioxide (CO_2) (Eggleston *et al*., 2006). Farm crops and animals contribute more than half of all people-induced emissions of N_2O world-wide (Mielenz *et al*., 2016). Farmland contributes about half of Australia's national N_2O emissions and, of these emissions, one third comes from nitrogen (N) fertilizers (Mielenz *et al*., 2016). The focus in this paper is on how much N_2O emissions and their associated externality cost is attributable to emissions from the N fertilizer used to grow fully irrigated cotton (*Gossypium hirsutum* L.) in New South Wales (NSW) and Queensland (QLD).

The approach used is from the ground up, based on the idea that to be usefully informative for decisions about efficient resource use and effective policy actions, estimates of the added externality cost of negative externalities arising out of economic activities need to be based on detailed, sound understanding of the system of production of the business entities causing the pollution. The boundary of this social benefit cost analysis is the nation and the focus is only on the direct emissions of N_2O from the N applied to cotton crops. This focus is on pollution by N_2O because it is primarily point-pollution and the likely quantities emitted can be estimated. As well, there is an established market price in CO_2 equivalents which represents the externality cost of the negative externality, from which can be calculated the externality cost of the global warming damage of the N_2O emissions.

The other significant forms of losses of N applied to cotton crops, such as ammonia polluting air and nitrates polluting water through leaching and run-off, are more difficult to assess and evaluate, and need to be done on a case-by-case basis. Pollution from nitrate losses can adversely affect the quality of water and as such is a genuine externality of N used to grow cotton: but since the effects are 'case by case', the variation in the costs can be extremely wide (Keeler *et al*., 2016).

Ammonia (NH_3) too is a major, mostly negative, externality from N use in agriculture. In the atmosphere it has a short life in which it can travel a range of distances (Air Pollution Information System, 2023). Shen *et al*. (2016) investigated NH_3 deposited within one kilometre of a commercial beef cattle feedlot and found that NH_3 concentrations in the air and deposits on the land decreased exponentially over one-kilometre distance from the feedlot. More significant, once in the atmosphere some NH_3 can transform into a fine ammonium NH_4^+ and, depending on velocity and timing of air movement, this pollutant containing aerosol can travel up to 1000kms. As explained in the Air Pollution Information System (2023):

> Atmospheric ammonia has impacts on both local and international (transboundary) scales. In the atmosphere ammonia reacts with acid pollutants such as the products of SO_2 and NO_X emissions to produce fine ammonium (NH_4^+) containing aerosol. While the lifetime of NH_3 is relatively short (and over a short distance) (<10-100 km), NH_4^+ may be transferred much longer distances (100->1000 km) (Asman *et al*., 1998; Fowler *et al*., 1998).

When NH_3 changes into NH_4^+ and becomes a much-travelled aerosol reaching large populations and adversely affects the health and shortens the life of some people, the addition to externality costs via this ammonia route is much greater than the global warming externality cost of N_2O emissions from the N used in agriculture.

An economic approach to estimating benefits and costs of fertilizer use uses marginal thinking and is forward looking; is centred on whole farm and value chain systems; estimates input production response functions and values the marginal production from extra units of the fertilizer; counts all costs including opportunity and time costs; has a relevant counterfactual; and estimates marginal emissions and values them using the market price of CO_2 equivalents. Total benefits are then estimated as the sum of the value of the marginal value products of each input of N fertilizer used.

The economic approach emphasizes the firm, the value chain and wider economy dynamics, where markets set the price of CO_2 (and equivalents) emissions and this price is the externality cost of the negative externalities.

Estimating Benefits and Costs of Nitrogen used to Grow Cotton in NSW and QLD

Nitrogen is but one input into a crop of cotton and the response to nitrogen added to a crop differs in different parts of paddocks, by whole paddocks, by regions, from year to year, on previous history of the use of the land sown to cotton, on timing and form of application of N, on use of other inputs such as irrigation water, on stored soil moisture and rainfall, on management skill, on timing of actions, on control of weeds and pests and so forth.

It is possible to consider the question of the benefits and costs of growing irrigated cotton in NSW and Qld using different perspectives:

- Identifying benefits and costs of the industry from an accounting perspective, where industry revenue and explicit costs determine the net surplus accruing to participants in the industry.
- Identifying benefits and costs from an economic perspective which is the welfare economics perspective, using the consumer and producer surplus and net social benefit of Social Benefit Cost Analysis. In this approach, consumer surplus derives from the marginal benefits from consumer demand, willingness to pay and the price elasticity of demand. Producer surplus is estimated with all costs being opportunity costs and marginal costs of supply derived from the price elasticity of supply. Aggregate benefit minus aggregate costs gives net social benefit, or, equally, consumer surplus plus producer surplus gives net social benefit.

The accounting approach estimates a monetary surplus added to the gross national product by the industry over a period of time. The accounting approach does not indicate the true benefits and costs of an activity because not all the benefits and costs of the activity are included in the analysis.

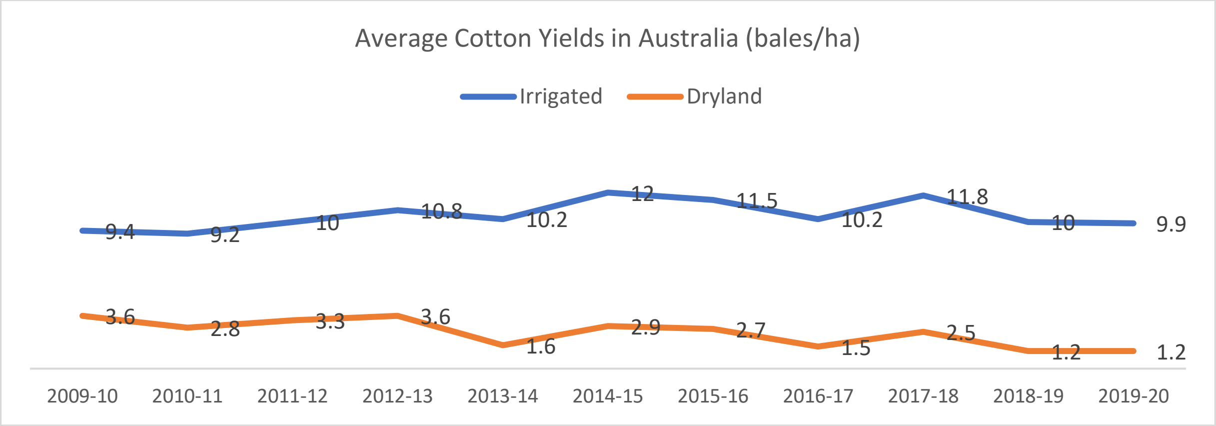
The economic approach estimates how much the economic activity at individual and industry level is adding to the individual and aggregate welfare. That is, after considering in a theoretically correct manner *all* benefits and *all* costs, how much the activity is making people better off in total, how much the activity is making people worse off in total, and thus the true contribution the activity is making to people's welfare – the net social benefit of the industry. The research reported in this paper is set firmly within the discipline and theory of welfare economics. The method used is Social Benefit Cost Analysis.

Analysing production of cotton in Australia and the benefit of N used and the cost of N_2O emissions involves understanding of the key principles of production economics. From the viewpoint of the individual farmer, the main principles are:

- The marginal product of an extra variable input, with all other inputs held constant and not limiting output, is the addition to total yield that results from the extra unit of variable input.
- The marginal cost of an extra unit of variable input is the extra cost of purchasing it and applying it, with supply of the input for the farmer being price elastic.
- The value of a unit of extra yield is the marginal value product which is the marginal product multiplied by the price of the extra yield, with price of yield received by an individual farmer being based on demand that is price elastic.
- Maximum profit from using a variable input with no other inputs limiting production is where the marginal cost of an extra unit of the variable input equals the marginal value product of the extra yield that results. This can also be expressed as Marginal Product = Price of N/ Price of Cotton.

Information exists from surveys and industry sources and science experiments about typical quantities of N used per hectare to grow crops of cotton. For example, annual grower survey reports by the Cotton Research and Development Corporation provide a wealth of detailed information about the operation and performance of cotton farms in the six cotton growing regions in NSW and QLD (Appendix A1 and A2). Results of these surveys over a run of years indicate how cotton yields and areas grown vary widely from year to year, and how much N was used per hectare on average in different regions. For example, the results of the 2017/18 survey of cotton growers in NSW and QLD revealed that for fully irrigated cotton the average yield was 11.22bales/ha. This result was an increase on the 2016/17 average of 9.99 bales/ha but less than the 2015/16 result of 12.4 bales /ha. In a typical good year around 280kg to 300kg/ha of N is associated with yields of around 9 bales, 10 bales, 11 bales, or 13 bales per hectare, depending on the myriad of other factors influencing response as outlined above. The annual average yields of cotton for Australia over the past decade are shown in Figure 1.

Figure 1. Average cotton yields, 2009-2010 to 2019-2020



Source: CRDC 2020 Grower Survey

Average data tells nothing about the marginal benefits of the N used in growing the crop. To estimate the total benefits of N applied to a crop requires an estimate of the marginal product of each unit of N, and the value of these, which is the marginal value product of additional N applied. This requires a cotton: nitrogen production function and estimates of the marginal product of additional units of fertilizer applied. The challenge is: which production function? In each paddock, in each region and in each time a different production response function will apply. How different is the performance of growing cotton in different regions at different times? The data from the annual cotton surveys (Appendix A3) indicates the average yields of cotton per hectare in any year are not markedly dissimilar in many of the regions, with similar increases and decreases in yields from best and poor crops of cotton.

To estimate production of cotton and associated emissions of N_2O in Australia in future years involves the following sequence of steps (restating some of the argument in Malcolm *et al*. (2022)):

A: Identifying the cropping rotations in which cotton is grown and estimating a probability distribution of the positions of a representative N: cotton yield response function, for a defined rotation that could occur annually in paddocks of cotton across NSW and QLD. A distribution of possible production response functions to N that could apply around the mean of the representative response function in different paddocks, regions and years encapsulates the real-world phenomenon that the extra yield from extra N in any year will vary by paddock, region, seasonal conditions, crop rotation and so on.

B: From the probability distribution of possible N response functions that could apply in any year for all fully irrigated cotton grown, a probability distribution of marginal products of N (MPn) for each level of N used can derived (marginal product is the slope or first derivative of the response function).

C: Distributions of the marginal (private) cost of nitrogen (MCn) using the range of prices of N fertilizer experienced in past years and application cost are established. Also, a distribution of the price of cotton (Py) is used, and a distribution of the Pn/Py ratio is derived (recalling that the theoretical profit maximizing level of N is where MPn=Pn/Py).

D: Using the information from steps B and C above, a probability distribution of theoretical profit maximizing levels of N used to grow cotton is estimated. This measure includes only the identifiable economic benefits from yield of extra N inputs. In practice an ‘insurance effect’ means farmers often use more N than the ‘theoretical profit-maximizing level of N’. Though the response function is flat around the optimum (Pannell, 2006), the added cost of seemingly ‘too much’ N is small relative to the cost of lost yield from ‘too little’ N. So, the range of possible N use is widened from the theoretical profit maximizing level for the representative response functions to the range of application levels farmers use in practice.

E: From the probability distribution of possible marginal products from applying N, the marginal product of N is multiplied by the price of cotton to derive a probability distribution of marginal value products (benefits) of N inputs to cotton. The total of marginal value products of N used is the total benefit to the farmer of using N to grow cotton. This total benefit is in the form of a distribution derived from the distribution of marginal products and the distribution of cotton prices.

F: From the most likely level of N use per hectare by farmers in a year, direct N_2O emissions per hectare can be estimated.

G: A cost (cost of negative externality) is placed on these emissions of N_2O from N applied per hectare to the cotton crop by drawing from a distribution of the possible market prices of carbon, i.e., the possible externality costs of CO_2 emissions.

H: From the emissions from the hectare of land that is part of the cotton crop and its associated rotation, the share of the emissions that is attributable to the cotton crop using the crop rotation-counterfactual (explained below) is identified. This externality cost is expressed per farm system.

I: A probability distribution of the range of total areas of cotton crop that could be grown each year in the future years is derived from information about total areas of cotton grown in NSW and QLD each year in the past decade.

The Counterfactual Required to Estimate the Additional Externality Cost of N_2O Emissions from Cotton[2]

Nitrous oxide emissions are a cost to the environment and the economy. There is a market value for this cost, the price of CO_2 equivalents is the measure of the cost caused by CO_2e in the form of global warming. From a decision and policy perspective, this raises the question about how much N_2O emissions from a cotton farm is directly attributable to that crop of cotton?

The question is: ‘How much N_2O does using N to grow cotton in Australia add to the atmosphere and add to the stock of global greenhouse gases and contribute global warming?’ Put another way: ‘How

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[2] See Appendix A4 for more information about counterfactual crop rotations.

much less would the global stock of greenhouse gases be if there was no cotton grown in Australia – or – if N_2O emissions from N used to grow cotton was reduced?'. These questions raise the perennial economic response when an alternative state of the world is considered: 'Compared with what?'.

For decision and policy purposes the relevant measure of the contribution of the activity of growing cotton to the global stock of greenhouse gases is ***not*** the total emissions of N_2O that result from applying 280kg/ha or more N to cotton crops. The relevant measure of the contribution to global greenhouse gases from N applied to cotton crops is how much N_2O is added by this practice compared with how much N_2O would be added if cotton crops were not grown or were grown using less N. The hectares of agricultural land currently used to grow cotton would have another use if cotton was not grown, and that use too would result in N_2O being added to global stocks of CO_2e, or cotton could be grown differently to emit a lesser quantity of N_2O.

Estimators of emissions of pollution with a focus on total emissions, and users of such estimates as guides to action, are employing the implicit counterfactual that the resources involved in causing the pollution in the *with* case would not be used at all in the *without* case. The counterfactual to assess the addition of N_2O to the atmosphere from growing cotton in Australia is the quantity of N_2O that would be emitted from each of the hectares currently growing cotton in a rotation if these hectares of cotton were instead used in an activity other than cotton or were used to grow cotton with less N and/or with N fertilizer that had less N_2O emissions.

Estimating Generalized Input Response Functions

For research purposes, a major question is 'What response function to use as representative of a wider area than one hectare in one farmer's paddock?' Response functions vary from place to place and from time to time. Generalized estimates of quantities of input use can be derived, for a year and for a range of years. In the dairy industry, Stott *et al*. (2018) developed a generalized N: pasture response function exhibiting diminishing marginal returns for dairying by using results from over 2,000 experiments from around Australia. The constant of the generalized function - the intercept - was able to be moved up and down according to the season and the region. Another approach was taken by Godard *et al*. (2008) who used linear programming models of representative farm systems in Europe and established plausible N response functions for these systems, for subsequent use in larger models for policy purposes. Godard *et al*. (2008) explained:

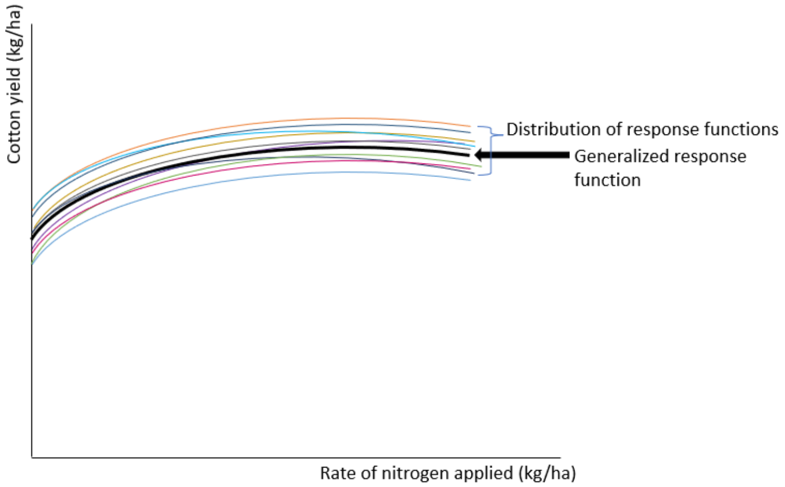
> 'The proposed crop management practices are mainly based on the ideal behaviour of the farmer who is assumed omniscient and able to detect every peculiarity of stress in his (sic) crops. As our approach is normative and based on a profit maximizing objective for farmers, it does not integrate other production decision processes of farmers in N-response curves, such as for example risk aversion' (p.73).

With fully irrigated cotton, though soil types differ, there is a certain degree of homogeneity in the crop system because of the partly 'controlled environment' resulting from having some control over available soil moisture. Timing and form of application of N and of weed and pest control matter too. The element of homogeneity of fully irrigated cotton production systems, and the similarity of costs and prices faced by growers, lends credence to the notion that generalizations can be made about N use per hectare on farms across the industry and across time. From this, estimates of the likely extent of yearly emissions of N_2O from a typical farm and the whole of the irrigated cotton area can be made, with areas varying per year depending on natural and economic conditions. The likely N_2O emissions and associated externality cost can be estimated over a defined planning period, for the industry as it currently is, or for a possible changed future industry.

In this study a representative N: cotton response function was developed from a variety of sources of information, for a fully irrigated cotton crop with cotton grown as a component of a rotation. The specified rotation was cotton in the spring, followed by wheat in the winter, then fallow over the summer after the wheat is harvested and back into cotton the following spring to start the next rotation. As shown in Figure 2, in this work the approach taken was to develop a representative nitrogen response function with a distribution around it. To this end, information from trials and experiments, from previously estimated and derived N: cotton response functions for fully irrigated cotton with the typical rotations, as well as expert advice from farmers, advisors and scientists was drawn on.

The response functions in Figure 2 represent growing irrigated cotton in the six cotton-growing regions of NSW and QLD, where different paddocks, farms and regions have their own response function at work in each season with different potential maximum yields. This allowance for a range of yields around the mean of the generalized response function captures two phenomena. First the true response function for any paddock or part of a paddock or a region is unknown and so a range around the generalized response results will apply, and different combinations of seasonal conditions suit different regions in different ways in different years. Further, distributions of prices of cotton, costs of N, marginal products, marginal value products and areas sown each year to cotton are used, not single values. Thus, all results are in the form of distributions, the result of thousands of runs of 'production year decisions' incorporating all the combinations and permutations of possible cotton prices, N costs, and areas sown that can be imagined for the future.

Figure 2. From distributions of response functions across seasons, farms, and regions into a distribution of a composite generalized response function



The N response function developed in this analysis started with the response function used by Welsh *et al*. (2015) (derived at the Australian Cotton Research Institute in the Lower Namoi Valley near Narrabri, NSW from a local experimental site for the cotton season 2013/2014). Experimental information came from response functions from experiments conducted at Gunnedah, NSW (Baird, 2016). Cotton industry survey data over six years was used also (CRDC, 2016, 2017, 2018, 2019, 2020, 2021)(see the Appendix).

The starting point response function by Welsh *et al*. (2015) was:

$$Y = - 0.209x^2 + 9.998x + 1978.8$$

where Y is yield in kilograms/ha and x is kilograms of N per hectare.

The marginal product is the first derivative of the response function:

$MPn = - 2*0.209x + 9.998$

The value of the marginal product is the MPn multiplied by the price of cotton Py.

The economic optimum quantity of nitrogen to apply is the quantity where the marginal cost (MC), the cost of a kilogram of N applied per hectare, equals the marginal value product. This economic optimum is given where MP=Pn/Py. The price ratio is given by the marginal cost of the fertilizer per kilogram and the cost of applying it, and the price per kilogram of cotton expected to be received net of any levies.

A range of alternative positionings of this curve, achieved by changing the constant in the response function, are used in this analysis which are consistent with evidence from trials, survey data and expert opinion about the range of responses to N that will occur where cotton is grown in NSW and QLD. The initial response function was adjusted downwards by a factor of 0.83 so that the N input calibrated with the survey data results for yield and input use across the broader regions of fully irrigated cotton production. A distribution of possible positions for this wider-area calibrated response function was formed, with a range of performance levels from 0.9 to 1.039 of the input: output levels of the calibrated function being possible in any year over runs of thousands of production years.

Once plausible information is obtained about the likely quantities of N fertilizer that growers of fully irrigated cotton are likely to use per hectare per crop, estimates can be made about quantities of N_2O emissions and the contribution that growing this cotton is making to global warming.

Estimating Direct Nitrous Oxide Emissions from Nitrogen Fertilizer on Cotton

The cost of N_2O emissions from N fertilizer applied to growing cotton can be calculated from the externality cost of the CO_2 equivalents arising from the N_2O pollution. The externality cost of carbon is given by the price established in markets for the right to emit CO_2 equivalents pollution into the atmosphere or equivalently the payment for removing CO_2 equivalents from the atmosphere. A distribution of possible values that the cost of CO_2 emission equivalents could take in any year is used to value the cost of the annual N_2O emissions in the year they are incurred.

Having determined some realistic ranges of optimum levels of N application that would apply across a distribution of possible response functions that could apply across the industry, the emissions of N_2O associated with these levels of application of N per hectare of cotton and per farm can be estimated. Various emissions equations exist to make this estimate.

Green House Gas (GHG) calculators and methods have been developed in Australia and internationally to quantify GHG emissions from various sources in agricultural industries, including growing irrigated cotton (Grace *et al*., 2016). Emissions are estimated at Tier 1, 2 and 3 levels and are global or country specific, regional specific and site specific, using estimated average emission factors and/or biophysical simulation models (Visser *et al*., 2014b). Various GHG calculators for Australia and other countries that are Tier 1 and 2, the Cotton GHG calculator, FarmGas GHG calculator, and Veggie carbon calculator, were explored by (Visser *et al*., 2014b) using irrigated cotton as a case study. Additionally, there is the Cotton Greenhouse Accounting Tool (Ekonomou & Eckard, 2022) and the Irrigated Cotton Calculator developed under the Emission Reduction Fund, both of which encapsulate additional sources of N_2O emissions from cotton crops.

Grace *et al*. (2016) looked into emissions for N_2O from clay soils in Australia's irrigated cotton industry. These researchers concluded that:

Based on eight studies with 27 individual treatments across the cotton industry of Australia, a two-component (linear + exponential) statistical model describes fertilizer-induced N_2O emissions at the lower N rates better than an exponential model and aligns with the emission factor (EF) using a traditional linear regression model. Where variable N rate information is explicitly available (e.g., farm or regional emissions reduction methodology or regional inventory data) the two-component (linear + exponential) model is recommended but should be capped at an EF of 1.83 per cent until additional observational data are available for rates in excess of 300 kg N /ha (Grace *et al*., 2016, pp. 602).

The 'two-component (linear + exponential) statistical model' Grace *et al*. (2016) developed is

$$\text{EF (per cent)} = 0.29 + 0.007\,(e^{0.037N} - 1)/N$$

Welsh *et al*. (2015) used the following emission equation developed by Visser *et al*. (2014a) to estimate N_2O losses from N used in cotton crops:

$$N_2O \text{ emissions} = 0.3926*(\text{Nrate}/10)\,\hat{}\,2 + 18.927*(\text{Nrate}/10)$$

The focus in this study is on the direct emissions of N_2O mainly through denitrification excluding other indirect N_2O emission pathways from water run-off, leaching and volatilization which are much less significant, from the N applied to cotton crops. The equations developed by Visser *et al*. (2014a) and Grace *et al*. (2016) that quantify direct emissions have been used below to estimate N_2O emissions.

A hectare of cotton receiving 280 kg N/ha would result in direct N_2O emissions equivalent to 840 kg CO_2e/ha (Visser *et al*., 2014a) or 1,423 kg CO_2e/ha (Grace *et al*., 2016). The N_2O emissions derived from the Visser equation gives higher emissions estimates than does Grace's equation at N rates below 253 kg N/ha while the N_2O estimates from the Grace equation (capped at 300kg N/ha) are higher than that of Visser equation when more than 253kg N is used.

In this analysis, the N_2O emissions and the associated social benefit-cost ratios of N used to grow irrigated cotton were estimated using the linear plus exponential equation developed by Grace *et al*. (2016). This equation gives EFs for different N rates, a superior method to using a constant average EF across N rates that would over-estimate and under-estimate emissions at low and high levels of N use.

Marginal Costs and Benefits of Using Nitrogen Fertilizer

Costs

The marginal private cost of using N fertilizer is straight-forward, being the cost of the N fertilizer itself, plus the costs of applying it. An additional marginal cost of using different quantities of N fertilizer per hectare is the additional variable costs associated with the additional yield that results from the additional N applied. This is primarily the additional cost associated with additional yield, the extra cost of harvesting the extra output that results from the added N and any directly yield related costs such as insurances or levies, storing and freight. Some other variable costs may be involved too, such as higher weed control costs or additional other nutrient costs associated with the higher yield crops that results from the higher N use.

In this analysis, only the added cost of the N fertilizer and cost of applying it, and the resulting externality cost of N_2O emissions, are counted in the marginal cost. This is because first, the yield response to N is based on there being an adequate supply of other required nutrients to achieve the extra yield and second, the additional cost of harvesting each extra tonne of extra yield is much less than the base cost of harvesting a base-level yield without N being used and diminishes rapidly as extra tonnes are harvested. Hence the interpretation of the benefit to cost ratio of extra N/ha is that only a small portion of the margin between total benefits and costs of N used per hectare would be required to cover these additional, but uncounted, yield-related costs of growing more product by using more N.

Benefits

The marginal value product of the N fertilizer to grow cotton is the benefit of N to the farmer. The marginal value product is estimated as marginal product of N at each level of N use multiplied by the distribution of values the cotton could take in the future, giving a distribution of marginal value products (MVP). The MVP from units of N above the cost of the input represents the users demand curve or 'willingness to pay' for extra units of the input, i.e., the sum they would be prepared to pay for each extra quantity of the input. The difference between the marginal value product of an extra unit of output and marginal cost of an extra unit of input is the extra surplus or net benefit each extra unit of an input adds to total surplus of a firm.

If the question is about the contribution the activity using this farmland to grow cotton makes to the welfare of the population, then the counterfactual approach, that was used to estimate the genuine addition of N_2O to greenhouse gases attributable to N use on cotton in a rotation, applies equally to the benefits of the cotton crop. Applying the counterfactual, the benefits from the cotton grown (sum of marginal value products from applying N) are the benefits above the benefits that would occur if cotton was not grown; that is, the benefits from the alternative crop in the cotton crop rotation, which for illustrative purposes in this case is defined to be a crop of sorghum[3] using a mix of rainfall and some irrigation depending on soil moisture and the water supply available for irrigation, as well as the price of water and the sorghum. In practice, any of a range of alternative activities to cotton in the rotation are possible and would apply in particular farm systems: the sorghum crop and the response functions used are but one possibility.

Benefit to Cost Ratio

In the case at hand, the cotton farmer's optimum quantity of N use per hectare includes perceived benefits other than the marginal yield and the value of the marginal yield that relate to risk and uncertainty about responses. The farmer's attitude to these risks and uncertainties, price, and marginal cost, means that they use on average around 280 kg N/ha, some 20-25 per cent higher than the theoretical 'economics only' economic optimum rate. An application of 280kg/ha of N has a mean private cost of $303/ha.

Before applying the counterfactual, at 280kg of N on cotton the mean total marginal value product of cotton is $2,856. Before considering the counterfactual, the private benefit of using the N is much greater than the private cost of $303/ha, with a benefit cost ratio of 8.6:1.

But there is more: a hectare of fully irrigated cotton receiving 280 kg N/ha would result in direct N_2O emissions equivalent to 1,423 kg CO_2e/ha, as derived using the N_2O emission equation of Grace *et al.*

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[3] A future counterfactual to the current situation of growing irrigated cotton could involve retaining cotton in the rotation and replacing a conventional N fertiliser currently being used with an Enhanced Efficiency Fertilizer that emitted 30 per cent less N_2O. The net effect on farmer welfare of using such an EFF, including that of producers of the EFF fertilizer, would be determined, the yield response function of the EFF fertilizer, the cost of it, the price of the cotton, and the N_2O emissions at the optimum rate of use of the EFF fertilizer. Then, at an industry, value chain and wider social level, the welfare effects of the EFF fertilizer would be determined by the cost, prices and quantities of the EFF fertilizer and the cotton which in turn depends on the price elasticities of supply and demand of the EFF product and the price elasticities of supply and demand of the cotton.

(2016). The corresponding cost of the negative externality of N_2O emission/ha, before considering the counterfactual at this farmer optimum rate of N use per hectare, is \$116/ha at a cost of \$80/t of carbon dioxide equivalent. When this externality cost is added to the private cost of N, the benefit cost ratio of the N used to grow the cotton and the private cost of the N used plus the externality cost of the N_2O pollution that results, before the counterfactual, is 6.2:1.

Now, consider the counterfactual comparison of one of the possible alternative activities for using the land, which would vary for each farm system. The cotton rotation of cotton-long fallow-wheat over two years could be replaced by a rainfed-irrigated grain sorghum-long fallow-wheat. The long fallow will have emissions, but with less N used than for cotton, maybe around 30 per cent of the emissions from the cotton crop. The fallow will be in both the cotton-fallow-wheat rotation and in an alternative crop-fallow-wheat rotation. Depending on rainfall and soils and quantity of nitrogen used, N_2O emissions from the crops of wheat vary from an average per unit of N applied of 0.02 per cent to 2 per cent (Barker-Reid *et al*., 2005; Mielenz *et al*., 2016; Officer *et al*., 2008; Scheer *et al*., 2012). This would be the same in each rotation with or without cotton. The rainfed plus some irrigation sorghum crop replacing the cotton crop will have less N used per hectare and less emissions than a hectare of cotton (Department of Primary Industries NSW, 2022).

Suppose in one such case that 120kg/ha of N was to be used on an alternative rotation sorghum crop, which could be rainfed or rainfed plus some irrigation[4] (Schlegel and Havlin, 2021), and which would be grown in place of cotton, and would produce a total MVP of N of \$754/ha. The sorghum crop emits N_2O at each level of N use in line with the N_2O emissions function from the crop of cotton, amounting to 167kg/ha of CO_2e and a lower externality cost of \$14/ha.

The aggregate marginal value product of N on cotton (the benefit) is \$2,856/ha. The aggregate marginal value product of the sorghum is \$754/ha. The externality cost of the N_2O emissions/ha of cotton is \$116/ha minus \$14/ha, giving \$102/ha. This means, only in this illustrative case, the externality cost of N_2O emissions that would be genuinely attributable to the N used to grow cotton and not sorghum in the current rotation, at a mean carbon price of \$80/tonne, would be \$102/ha. If this was the actual counterfactual, for an average farm with 576 ha of cotton, the negative externality cost of that crop would amount to near \$58,800. The net social benefit of the cotton grown, or gross addition to welfare, would be \$0.9m/farm from that crop. The social benefit to cost ratio from the benefits/ha of cotton to the private cost and externality cost/ha, with the counterfactual crop used in the analysis, would be 7.2:1.

If in the case where the alternative use of the land in the no-cotton rotation had zero N_2O emissions, then the cotton crop would be accountable for its full share of N_2O. Cotton would be responsible for an externality cost of \$116/ha at the mean carbon price of \$80/t.

Uncertainty

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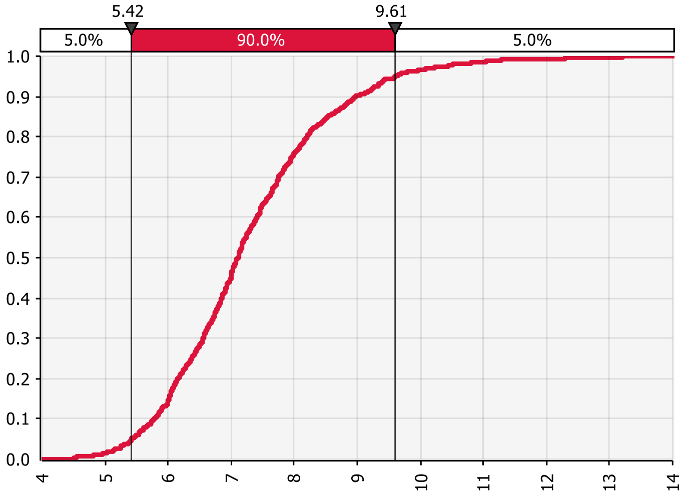
[4] Grain sorghum is used in the analysis as the counterfactual crop for growing cotton in NSW and QLD. Grain sorghum can be grown on stored soil moisture and growing season rainfall alone or with added varying quantities of irrigation water, commonly achieving yields of 2t/ha on dryland to 8 tonnes/ha on full irrigation and depending on seasonal water availability and crop situation, 3,4,5t/ha too – averaging across total production around 3t/ha. The response functions of grain sorghum to N use vary considerably from paddock to paddock and season to season, depending on the soil types, previous crops in the sequence, annual growing season rainfall, weed and disease control, the grain protein, planting details of rows and seed density and so on. Using a response function generalized to apply to the whole area of sorghum grown under a range of ways, where the typical average production is 3t/ha across the total area grown, and with grain sorghum price \$300/t and nitrogen application cost around \$1, the economic average optimum application of N over total area of sorghum grown would be around 120kg/ha.

Figure 3. Probability distribution of benefit cost ratio obtained using @Risk software



There is uncertainty about elements of the analysis conducted hitherto, such as the response function and yields, the emissions function and the N emissions at different levels of N/ha, the prices of the cotton, and the costs of the N. Probability distributions attributed to each of these variables in the analysis enable estimation of a probability distribution of the social B:C ratio of N used to grow irrigated cotton in Australia. This probability distribution of the benefit cost ratios for different combinations and permutations of the levels of the main uncertain variables is shown in Figure 3.

Under the assumed probabilities for the values the key uncertain variables could take, with only direct N_2O emissions counted as the negative externality of the N used, there is a 90 per cent probability that the Benefit to Cost (B:C) ratio of N used to grow cotton is between 5.4:1 and 9.6:1. There is a 55 per cent chance the B:C ratio would be more than 7:1. There is zero chance the B:C ratio would be under 4:1.

Information about aggregate benefits and costs to help inform policy considerations: Whole industry aggregate social benefit and social cost (private plus externality) of the cotton industry with one possible counterfactual activity

Looking to the whole industry for the purposes of putting the benefits of the economic activity and the external costs of the N_2O pollution it contributes to global stocks means summing the situation of the representative cotton farmer up to industry scale. Again, when the question is about the contribution of net social benefit to aggregate welfare that is made by the activity of growing a cotton crop using N (after counting all benefits and all costs including opportunity costs and negative externality costs of emissions of N_2O), then the counterfactual is relevant: this is the total benefits and total costs of the crop rotation with cotton compared with the total benefits and total costs of the crop rotation without cotton.

The area of cotton grown in any year in NSW and QLD varies widely as the decision to grow cotton is determined to a large degree by the amount of stored soil moisture, the expected availability of irrigation water and the evidence about the possible rainfall to anticipate in the growing season. The anticipated price of cotton too is influential. At industry level, the price elasticity of demand is key to determining the size of consumer surplus. In the case of the almost wholly exported cotton, demand is price elastic and the world price is used, meaning there is no consumer surplus, only producer surplus that constitutes total benefits.

Over the past decade the area of cotton grown each year in NSW and QLD has varied from 70,000 hectares in 2019/20 to 600,000 hectares in 2011/12, with several years in which around 400,000 hectares was grown (CRDC, various years), as shown in the Appendix. The area of fully irrigated cotton grown each year varies widely. Estimating the possible size of the industry-wide annual externality cost that could be added to total externality cost by cotton-growers' use of N, and the size of this annual addition to the externality cost relative to the private benefits, requires a discounted cash flow approach. A real 5 per cent discount rate was used to evaluate the externality cost of emissions from N used to grow cotton over the next 15 years. Possible areas of annual cotton crop were selected from a truncated normal distribution ranging from 70,000 ha to 600,000 ha with an annual mean area of 380,000 hectares and with 85 per cent of this being used to grow fully irrigated cotton.

The mean industry total net social benefit after deducting the private cost of extra N use and externality cost from N_2O emissions from N used in fully irrigated cotton production can be estimated for the scenario where:

- the distribution of the number of hectares in future did not change from the past pattern for the next 15 years,
- nothing changed about the current farming system, inputs, and outputs,
- the externality cost of N_2O emissions came from growing fully irrigated cotton using on average 280kg/ha of N,
- the same counterfactual as used above,
- mean emissions cost from cotton is $104/ha/year, and
- carbon costs ranging from $50/t to $120/t and averaging $80/t.

In present value terms at 5 per cent real discount rate per annum, the mean net social benefit is the present value of the extra social benefit from the extra N minus the mean present value of extra social cost of the extra N. This gives a mean net present value (addition to net social welfare) of $6.9 billion over 15 years, or a mean annuity value for addition to net social welfare after the externality cost of N_2O emissions, at 5 per cent real discount rate, of $541 million. For this 15-year scenario, the mean ratio of present value of private and social benefits of N to private and externality costs of N is 7.3:1. Looking at the probability distribution of the ratio of social benefit to the externality cost of the N and its negative externality of N_2O, there is a 90 per cent probability for the B:C ratio to be between 5.5 and 9.4, and a 57 per cent chance the B:C ratio would be greater than 7:1.

Policy Implications

Market failures that are worth fixing require public action. The first point to make is that policy analysis requires sound estimates of the sources and magnitudes of the likely future externality costs of the market activity in question. Estimates of the externality cost of a market failure in the form of a negative externality can be done from the perspective of 'this is the apparent externality cost considering the counterfactual to the economic activity *before* any policy is introduced to correct the market failure'. This is the basis of the estimates of the externality cost of a negative externality in this research[5].

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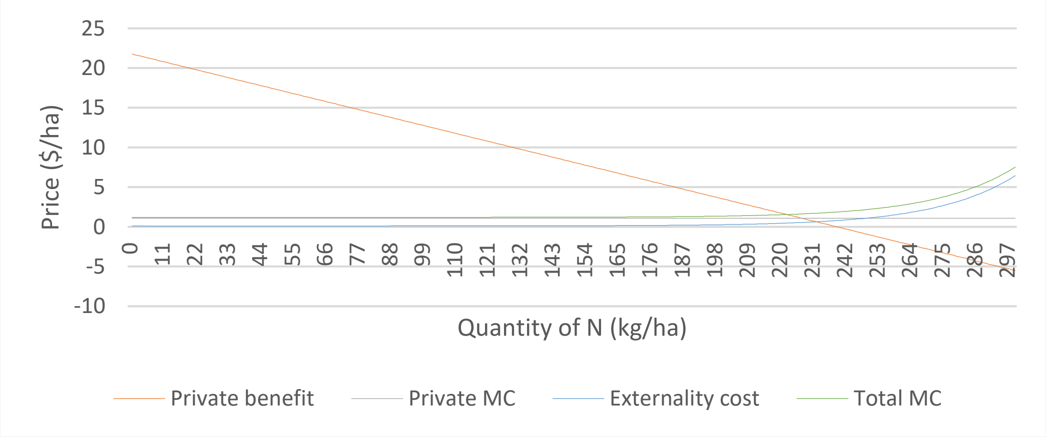
[5] Alternatively, the externality cost could be evaluated from the perspective of the whole economy where the externality cost in the economy is estimated as being the cost imposed on society including the expected cost of fixing it. The difference between society's net social welfare *before* policy to ensure externality costs are counted and society's net social welfare *after* externality costs and benefits are counted in production and consumption decisions and policy is enacted, encapsulates dynamic adjustments in the economy that are involved and includes the costs and benefits of fixing the market failure. Importantly, this estimate of the expected externality cost of a market failure also recognizes that policy is only about fixing market failure up to

What would happen to grower demand for N if the externality cost of N_2O emissions from the N input was added to the cost of the N fertilizer to the farmer, or deducted from the price paid for cotton to the producer, as part of a 'make the polluter-pay' policy?

A guide to producer response would be the effect when including the externality cost of N_2O when the economic optimum amount of N is used. The marginal value product of N represents the farmer's demand for the input. As the externality cost is added to the private marginal cost of nitrogen at each level of N input up to the private economic optimum quantity of 227 kg/N/ha, the social optimum rate of nitrogen takes a value slightly less than the private economic optimum rate.

As depicted in Figure 4, when the externality cost of the direct emissions of nitrous oxide that add to global stocks of CO2 are added to the cost of nitrogen fertilizer used to grow the cotton, this amounts to a 'tax' of $0.50/kg N, which is fully borne by the farmer. This extra cost increases the marginal cost of N to $1.5/kg N, the optimum nitrogen rate for the farmer and society declines from 227 kg N/ha to 223 N kg/ha. This is because the price elasticity of demand for nitrogen fertilizer is very low, with a 50 per cent increase in the price of the nitrogen causing a 2 per cent reduction in the demand for nitrogen as per the calculation here. The reason for this is that the total marginal value product of nitrogen is high over most of the range of use of the input. This is because the marginal benefits of N in this range of use of N is so substantial relative to any added cost. The same analysis, with the burden of the externality cost deducted from the price of cotton the farmers face gives the same result.

Figure 4. Change in private benefits, private marginal cost, externality cost and total marginal cost with rate of nitrogen fertiliser use



Support for there being low elasticity of demand for key inputs to production with high marginal value production is not hard to find (Griliches, 1958, 1959; Heady & Yeh, 1959; Rausser & Moriak, 1970; Wright *et al*., 2018). Breen *et al*. (2012) found farmer demand for N in Ireland was price inelastic and cited work by Boyle (1982) and Higgins (1986) with similar findings. Breen *et al*. (2012) cited Burrell (1989) finding 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. Breen *et al*. (2012) had a price elasticity of demand for N of -0.39. In a US study Williamson (2011) estimated price elasticities of demand for N ranging from -1.67 to -1.87.

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the point where the benefits of doing so exceed the costs, i.e., removing externality costs that are worth removing.

Real world evidence of this phenomenon of the demand for the N input to production being unresponsive to incentives is evidenced by the existing policy measure, the Emissions Reduction Fund, which offers the opportunity for cotton growers to take out a contract and be paid for them reducing the N_2O emissions their crop rotation contributes to greenhouse gases. This Emissions Reductions Fund opportunity has existed since 2015. Not a single contract to do this has been taken out by cotton growers (Emissions Reduction Fund, 2022).

The implication of a low-price elasticity of demand for an input is that a large rise in the cost of the input will not cause a similar-sized reduction in its use. Guha and Wright (2016) cited an example where a 500 per cent tax on phosphorus was estimated to cut use of the input by 8 per cent. The same point about unresponsiveness of N use to changes in the price of N was made by Welsh *et al*. (2015) after performing sensitivity analysis on a range of costs of nitrogen and N responses. Looking internationally, Pearce and Koundouri (2003) cast doubt on taxing fertilizer inputs as a solution to a nutrient pollution problem because over the range of input use where low price elasticity of demand prevailed meant such taxes on low responsive inputs need to be high as a proportion of the marginal private cost of the input to effect significantly the quantity of the input used. This would suggest that if the farmer has ample incentive not to change their production system to accommodate the added externality cost of their production, they also have ample financial capacity to pay someone who is better placed to reduce CO_2e emissions to do this for them.

A different take on this question emerges when the N use is at a level where yield (and MVP) responses are low and N_2O emissions start rising rapidly. Apart from the finding of Grace *et al*. (2016), Shcherbak *et al*. (2014) conducted a global meta-analysis of the non-linear response of soil nitrous oxide (N_2O) emissions to fertiliser. These researchers concluded that there was mounting evidence that the emission response to increasing N input was exponential rather than linear.

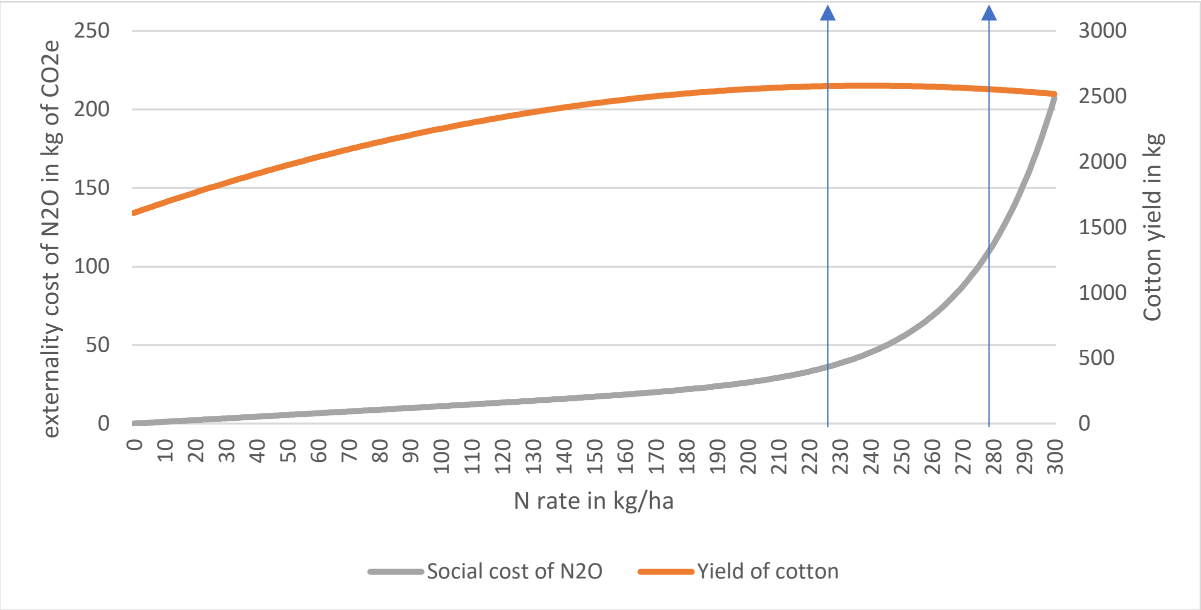
In Figure 5 is a graphical depiction of the changes in cotton yield and the externality cost of N_2O emissions when direct emissions increase exponentially as nitrogen use rates go beyond an initial range of typical application rates. The response function of cotton tends to get flatter at N rates above 230kg/ha whereas the N_2O emissions cost tends to increase exponentially above around 250 kg N/ha. This means the externality cost of the emissions follows a similar sharply increasing trend.

In practice, cotton growers typically use around 50kg/ha more than the theoretical economic optimum because of other perceived benefits; their use of N reflects a 'farmer optimum' where other, non-priced benefits are perceived and these are to do with uncertainty and risk about how the season and prices will turn out and the chance of missing out on an opportunity if N were to be the 'limiting factor' in the performance of the cotton crop. The farmers are acting to avoid the chance of either 'using too little' and/or missing out on yield if the season turns out very favourable.

At 280 kg N/ha applied to the cotton crop, the growers are operating on a flat part of the most likely yield response function but would be on a steeper part of a higher performing production function if the season turned out better than typical.

The theoretical economic optimum level of N application of 227kg N/ha, is estimated for an 'expected value' response function and defined expected monetary benefits and costs, the externality cost of the N_2O emissions is around $30 ha. From about 230kg N/ha, the farmer spends another $50/ha on N as 'insurance' to help cover for remaining uncertainty about benefit in some years. In some years, the $50/ha might deliver no extra output, but the farmer had the benefit of the having some 'insurance N'. But the extra 50kg of N above the economic optimum adds around $80 externality cost from N_2O emissions. Of the total externality cost of N applied to the hectare of cotton of $116 ($102 after the counterfactual), \$80 extra externality cost is incurred at levels of use of N mainly determined by factors which may of a risk management nature.

Figure 5. Cotton yield response and N_2O emissions to nitrogen fertiliser use



At the highest levels of N use there would be a level of use, in this case between 230 kg N/ha and 280kg N/ha or beyond, where the extra externality cost of the extra N use being borne by the grower would outweigh the extra monetary benefit it delivers, and possibly, could also outweigh some of the extra risk-related benefits that growers perceive and which motivate them to use N beyond the optimum of around 230kg N/ha.

The response by farmers would likely be considerably more responsive beyond the level of N use where the yield and MVP response is small and where the N_2O emissions ‘take off’ and the externality cost of emissions rises rapidly. Around the highest levels of N use, if the externality cost was borne by the polluters, some farmers would face considerable incentive to restrain their use of N below this level and operate perhaps closer to the economic optimum level. Sacrifice could be minimal relative to the externality cost avoided. More generally, though not for export-orientated cotton, the full burden of an exponential N emissions effect would also depend on whether a portion of the extra externality cost is able to be passed forwards to consumers as well.

Who pays?

The question of who would pay for an added cost of production or consumption, such as the externality cost of N_2O emissions, can only be answered by considering the responsiveness of producer demand for the input and consumer demand for the output to the change. Economic theory and practice dictate that the ultimate sharing of extra costs between producers and consumers is determined by the relative responsiveness of demand and supply to these extra costs. If consumer demand over a range of prices declines less in response to the added cost than farmer demand for the N input declines, then the larger share of the total of the added externality cost burden is borne by the consumers of the product, not the producers[6].

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[6] A part of the story with cotton is the role of substitution between synthetic fibres and cotton in use, with the production of synthetic fibres involving high energy and CO_2e emissions. Analysing the effects of a charge for carbon emissions on cotton would need to be in the context of substitute synthetic fibre production also paying its carbon cost way.

In the case of cotton produced in Australia where 99 per cent of the lint is exported, and if other cotton producers around the world were *not* paying for their contribution to the externality cost from their N_2O emissions, then cotton producers in Australia would bear *all* their contribution to the externality cost. This would be because Australia's cotton producers who face a highly price elastic demand for their product on export markets would not be able to pass it onto buyers who would be able to buy what they need from Australia's now relatively cheaper competing suppliers of cotton. If cotton producers all over the world were charged the externality cost of their N_2O emissions, the result would be different. Under these circumstances, consumers around the world would pay a share of the externality cost caused by producing their product. This result would also depend on the responsiveness of demand by consumers of cotton for alternative products to cotton, and if producers of these alternative products too were paying for their contribution to externality cost from N_2O emissions.

Regardless, even if fully borne by producers of cotton, the relative magnitude of the possible externality cost of direct N_2O emissions from using N to help grow fully irrigated cotton in Australia is small relative to the total benefits of the nitrogen input. At $100/ha out of a gross margin/ha of say $2500, it would be a small share of gross margin per hectare too. Relatively minor gains in productivity and cost efficiency in the farm system would cover the added cost burden that was the externality cost of the contribution N_2O emissions from N used to produce fully irrigated cotton makes to global warming.

Conclusion

Estimating with rigour the externality costs of the direct emissions of N_2O from the nitrogen used to grow fully irrigated cotton in Australia provides useful information for producers, consumers, and policymakers pondering how best to go about reducing the pollution and paying the externality costs arising from this activity. Key to policy that would effectively reduce N pollution are credible estimates of N response functions and N emissions functions. Together these two pieces of information form the foundation for analysing how cotton farmers using N to grow crops could respond to policies to reduce nitrogen pollution. The methods used in the analysis are a guide to how to use the principles of welfare economics to analyse private and social benefits and costs of economic activities, and identify possible responses of producers, all to inform answers to questions about appropriate policies to reduce pollution.

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Endnote

We asked a non-economist about the benefits and costs of using nitrogen (N) to grow irrigated cotton in Australia: how much was used and how much the nitrous oxide (N_2O) emissions from the N fertilizer would be adding to the externality cost of global warming. The non-economist said: 'The total benefit of using nitrogen to grow cotton is the total revenue from the market value of the extra cotton grown from applying the 280kg of N/ha that is used. The yield of cotton is on average 11 bales/ha when grown with N, 4 more bales of cotton than can be grown without N. At an average price of $620/bale, this gives a total benefit of $2,480/ha. For an average cotton farm growing 576 hectares annually, this is a total benefit of around $1.4m. The total private cost of this N is $300/ha or $173,000/farm. At an average of 1 per cent emissions of N_2O *per kg of N fertilizer, 280kg N/ha gives off 1,320 kg/ha of* CO_2e*. At an average carbon price of $80/tonne, this adds an average $105/ha to the externality cost of global warming or $60,500 per average farm per year'.*

We asked a cotton farmer the same questions about how much N_2O *emissions there might be from the N fertilizer they used. The farmer said: 'Cotton is not grown as a single continuous crop, it is part of a rotation of activities, so the rotation of the crop of cotton is the focus. The marginal benefit of the cotton grown using N is the sum of the market value of each extra unit of cotton output (marginal product of nitrogen multiplied by the price of cotton) that is added by each extra unit of N input used. Applying 280kg of N/ha to the annual irrigated cotton crop component of my cotton-fallow-wheat rotation, using average prices, would produce marginal products per unit of N multiplied by price totalling $2,856/ha marginal value product of N, or $1.645m per average-sized 576 ha. farm. Producing this total of marginal benefits entails spending a private cost of $300 on 280kg of N used per hectare of cotton. Using an exponential function for the emissions of* N_2O*, the predicted total emissions from the hectare of cotton grown is 1,423kg of* CO_2e *per hectare, with these emissions rising rapidly beyond around 230kg N/ha. If I didn't grow cotton in that component of the rotation, I would grow a crop of sorghum instead, rainfed and with some irrigation in my system, and with lower gross income per hectare and using less N/ha. than the cotton. With the rest of the rotation staying the same whether cotton or sorghum is included in it, and if I was to use around 120kg of N to grow the sorghum crop in the rotation in place of the cotton crop, this would produce benefits of $754/ha and at the rate of N/ha used would emit 167kg/ha of* CO_2e *per hectare with an externality cost of $14/ha on* N_2O *emissions'.*

So, in this case, the hectare of irrigated cotton crop would return $2,100 above the benefits of the alternative crop and would add 1,256kg of CO_2e *to the global stock of* CO_2e *above the emissions that would come off the alternative crop. At an average $80/t of* CO_2e*, this would mean that in that year growing the cotton crop would add $102/ha or $58,800 per farm per annual crop of additional externality cost to the total externality cost of global warming, if the farmer was unable to pass some of this onto the consumer and had to bear the full cost. With a different alternative use of the land growing cotton, the extra social cost from* N_2O *pollution attributable to growing the cotton would be different. This is a case-by-case question. If the alternative to cotton was an activity that used no N, then cotton would be responsible for the full addition of* CO_2e *from the* N_20 *emissions from the N used. It depends.*

The farmer continued: 'Once we know the possible total and marginal externality costs being caused by the emissions of nitrous oxide and attributable to the N used on cotton crops, there is a basis for analysing possible public policy actions affecting the use of N on growing cotton to correct for this polluting failure of the private market. As happens, in my case, the marginal 50kg of N/ha I use on the cotton contributes most of the added externality cost from the N_2O *emissions. If the benefits I get from this last 50 kg of N/ha are more than the added externality costs from it, I could cover the added externality cost if I had to do so, and still be better off. Or, if the added externality cost is more than the marginal benefit from the last 50 kg of N/ha, then I could reduce the N I use by this 50kg N/ha, and so avoid the externality cost burden associated with this N and be better off. Alternatively, if I had to account for the addition to externality cost from N emission from growing cotton, and there was an enhanced efficiency N fertilizer (EFF) that had say 30 per cent less* N_2O *emissions, and if in the unlikely case this EFF performed the same in every other respect as my current N fertilizer, then I could cut* N_2O *emissions by 30 per cent by using the EFF'.*

There is an issue with the way the non-economist cited above is perceiving and analysing the question of 'How much CO_2e *emission comes from growing cotton is the relevant measure to inform policy formation?' compared with the way the farmer addresses the same question. The non-economist is being a theoretical empiricist,* *getting what 'the facts of the matter' and doing some accounting. They are using average and total analysis, with no explicit counterfactual scenario. They are valuing each unit of extra output induced by the N at the market price per unit (without the concept of producer and consumer surplus), whereas the market price is the value of the last unit of output sold in a market. Further, this approach is using an implicit counterfactual which is that if cotton was not grown, there would be no emissions of* N_20 *and* CO_2e *attributable to the hectare of cropland in question.*

In contrast, the farmer is doing economics; more specifically, social benefit cost analysis which is grounded in welfare economic theory. They are using marginal analysis, which is relevant for policy analysis and is about how much better or worse off society will be, what could be, what happens, if a bit more or a bit less was N used and cotton produced? Economic approaches are counting the true value of the extra output that is directly attributable to each extra unit of N by estimating the marginal product of each extra kg of N and valuing each additional extra output and using the concepts of producer and consumer surplus. They are applying an appropriate counterfactual for the emissions pollution situation in which cotton is not grown. They are attributing marginal emissions of N_2O *estimated by using an exponential rate of emissions from marginal additions of N fertilizer.*

The telling point is that estimates of the policy-relevant benefits and costs of using N to grow agricultural commodities will be different when using welfare economic methods compared with the estimates that come out of empiricism and accounting. In the example above, in terms of defining and describing reality to inform policy actions, compared to the welfare economics approach the accounting approach achieves the dubious double of getting wrong both the benefits attributable to using the land to grow an annual cotton crop and estimating the true N_2O *externality costs attributable to doing so. Estimates of benefits and cost that are not well-grounded in welfare economics theory misrepresent reality and misinform policy.*

Appendices

Appendix A1. N application rates on fully irrigated cotton (2020 – 2017)

Year reported	2020	2019	2018	2017
Season	19-20	18-19	17-18	16-17
Australia	253.4	325.1	335.9	298
Central QLD	258.2	331.4	296.9	310
Darling downs	190.9	205.8	235	288
Macintyre Balonne	306.8	398.4	366.2	346
Northern NSW	255.9	265.6	282.7	295
Macquarie	280	324.3	420.8	298
Southern NSW	277	443.5	396.7	324

Source: Cotton grower surveys 2021-2017

Appendix A2. Areas under cotton in Australia (2021-2014)

			Total area or average area per farm	Fully irrigated cotton	Partially irrigated cotton	Dryland cotton
2021	2021-21	Average	700 ha per grower	74 %	11 %	15 %
		Central QLD	457 ha per grower	67 %	20 %	13 %
		Darling Downs	323 ha per grower	61 %	16 %	23 %
		Macintyre Balonne	1,412 ha per grower	79 %	13 %	8 %
		Northern NSW	781 ha per grower	69 %	12 %	19 %
		Macquarie	596 ha per grower	98 %	2 %	-
		Southern NSW	562 ha per grower	100 %	-	-
2020	2019-20	Australia	69, 394 ha	25 %	24 %	3 %
2019	2018-29	Australia	205, 859 ha	37 %	11 %	13 %
2018	2017-18	Australia	501, 811 ha	45 %	24 %	12 %
2017	2016-17	Australia	509, 876 ha	53 %	39 %	18 %
2016	2015-16	Industry total	85,661 ha	62, 844 ha	9, 282 ha	13,535 ha
		Central QLD	6, 142 ha	5, 342 ha	600 ha	200 ha
		Darling Downs	9, 257 ha	5, 447 ha	670 ha	3, 140 ha
		Macintyre Balonne	16, 531 ha	15, 175 ha	331 ha	1, 025 ha
		Northern NSW	30, 188 ha	14, 095 ha	7, 051 ha	9, 042 ha
		Macquarie	4, 833 ha	4, 075 ha	630 ha	128 ha
		Southern NSW	18, 710 ha	18, 710 ha	-	-
2015	2014-15	N/A				
2014	2013-14	Industry total	70, 754 ha	60, 584 ha	4, 665 ha	5, 505 ha
		Central QLD	6, 149 ha	4, 529 ha	1, 500 ha	120 ha
		Darling Downs	4, 867 ha	2, 152 ha	1, 445 ha	1, 270 ha
		Macintyre Balonne	29, 238 ha	24, 103 ha	1, 620 ha	3, 515 ha
		Northern NSW	4, 568 ha	4, 438 ha	100 ha	30 ha
		Macquarie	4, 568 ha	4, 438 ha	100 ha	30 ha
		Southern NSW	13, 491 ha	13, 491 ha	-	-

Source: Cotton grower surveys 2021-2014

Appendix A3. Yields of cotton (2021-2016)

Year reported	2021			2020			2019			2018			2017			2016		
Season	20-21			19-20			18-19			17-18			16-17			15-16		
	Lowest	Average	Highest	Lowest	Average	Highest	Lowest	Average	Highest	Lowest	Average	Highest	Lowest	Average	Highest	Lowest	Average	Highest
Australia	10.38	11.88	13.13	9.24	10.45	11.55	8.53	10.23	11.95	9.46	11.22	12.61	8.22	9.88	11.07	3.7	12.4	15.7
Central QLD	11.59	12.76	15.32	9.78	10.86	12.07	9.14	10.01	11.6	7.71	9.62	11.73	7	8.81	10.21	3.7	8.6	11
Darling downs	10	11.27	12.38	9.33	10.66	11.96	7.58	9.34	10.96	7.68	9.04	10.84	5.92	8.05	9.44	6	12.1	14
Macintyre Balonne	11.39	13.27	14.52	9.45	10.85	11.96	7.98	9.94	11.36	9.02	11	11.97	8.88	10.85	11.42	6.4	13.4	10
Northern NSW	10.19	11.81	12.78	9.46	10.4	11.31	8.1	9.98	12.18	9.24	11.07	12.31	9.87	10.92	11.93	9.8	12.8	15
Macquarie	12.24	13.92	15.07	8.45	10.25	11.37	10.35	11.94	13.25	13.12	14.48	15.94	9.33	10.93	11.97	13	14.4	15.7
Southern NSW	9.09	10.66	12.29	8.65	10.42	11.92	8.64	10.42	12.07	9.54	11.32	12.79	7.7	9.5	11.15	10.5	12.7	14.8

Source: Cotton grower surveys 2021-2016

Appendix A4. Crop Rotations for the Counterfactual

The performance of a cotton crop cannot be analysed in isolation from other components of the system in which the crop is grown. Crops of cotton are fitted into cropping systems in rotation with other crops that complement cotton production, and for other benefits to the whole business such as income stability. Complementary rotation crops for cotton include summer oilseeds like soybeans, summer coarse grains like maize or sorghum, summer grain legumes, winter pulses like chickpeas or fava beans, green manures such as vetch, perennial legumes like lucerne, winter oilseeds like safflower, winter cereals such as wheat or barley, and bare long fallow to store soil moisture and break disease cycles. Winter cereals have sowing times that align well with the cotton growing season and harvest time and provide a strong disease break, as does long fallow.

The economics of crop systems are analysed using the concept of a rotation-hectare (Malcolm *et al*., 2005). For example, the gross margin of a cotton crop might be $400/ha, but this information alone is no guide to action. Growing the crop of cotton involves accompanying activities on the same piece of land at different times, such as a time of fallow on that hectare or a cereal crop to break a potential cycle of crop and soil disease, or a legume crop to rebuild soil N. The whole crop system is the entity for analysis of aspects of the performance of a crop, as well as for farm decision-making and public policy purposes.

The characteristic of the crop rotation of interest here is the N_2O emissions from all the activities in the crop system or crop rotation. First the N_2O emissions per rotation-hectare from the crop rotation used to grow cotton is estimated. Second, the N_2O emissions are estimated that would occur from the alternative crop rotation hectare that would be grown if cotton was not grown or if the cotton crop component of the same rotation was grown with more efficient fertilizers that emitted less N_2O. The *difference* between the N_2O emissions/rotation-hectare of the current rotation-hectare *with* cotton, and the N_2O emissions/rotation-hectare of the alternative rotation *without* cotton or with more efficient, less polluting cotton, is the correct measure for decision and policy purposes of the N_2O a current cotton crop adds to the stock of global greenhouse gases.

If the alternative rotation-hectare activities to the cotton rotation-hectares was an activity involving zero additional applied N and zero N_2O emissions, then the total of the N_2O emissions from the cotton crop would be the total addition of N_2O to the global stocks of GHG that would be attributable to growing cotton.

Once the addition of N_2O after the counterfactual that growing cotton makes to the stock of global warming gases is determined, the externality cost this causes can be estimated for policy purposes. Making this estimate is straight-forward, with N_2O having an equivalent global warming potential that is 300 times that of CO_2. The N_2O emissions are converted into CO_2 equivalents. These CO_2 equivalents cause an externality cost, the size of which is measured by the market price of a traded tonne of CO_2.