Australasian Agribusiness Review
2024, Volume 32, Paper 1
ISSN: 1883-5675

A Critical Review of the Effectiveness of Policies to Reduce Nitrogen Fertilizer Pollution

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Abstract

The increasing global population and consequent growing demand for food are causing more nitrogen (N) fertilizer to be used in agricultural industries. Although using N fertilizer significantly increases global food production, excessive application of N fertilizer pollutes the natural environment, contributes to the global stocks of greenhouse gases and global warming, and poses threats to human health. Governments worldwide have tried a range of policies to reduce these negative impacts of N fertilizers. There are few studies about the effectiveness of these policies. In this paper, a systematic review of the literature was done. Published findings about the effectiveness of policies that have been used or proposed to reduce pollution from N fertilizer have been summarized and synthesized. This information can help inform policymakers and enable them to assess better and measure the effectiveness of policies to reduce N fertilizer pollution. This would increase the chances of effective policies being adopted.

Keywords: Nitrogen fertilizer, pollution, effectiveness, policy

Introduction

The widespread use of synthetic N fertilizers has improved crop yields significantly worldwide (Frink *et al.*, 1999). In the past 60 years, the quantity of N fertilizer used has increased more than tenfold (from 10 million tonnes in 1961 to 111.6 million tonnes in 2022) and tripled global food production (FAO, 2022; Janssen, 2006). More than half of the global population is fed by crops grown using synthetic N fertilizers (Ladha *et al.*, 2005).

While N fertilizer increases crop yields and helps alleviate global hunger, not all of it is used by plants. Some N fertilizer is lost to the natural environment, polluting the environment and threatening human health (Pannell, 2017). A portion of N fertilizer is lost to the environment through denitrification, volatilization, immobilization, leaching, and runoff in the forms of nitrate, ammonia (NH3), nitric oxide (NO), nitrous oxide (N2O), etc. (Sutton *et al.*, 2019; Sutton *et al.*, 2011). The adverse effects of these N fertilizer pollutants include:

- Air pollution: Nitrogen oxides and aerosol particulate matter (PM) formed by N fertilizer loss pollute the air and increase the risk of respiratory diseases in humans (Sutton *et al.*, 2013).
- Greenhouse gas emission (GHG): Agricultural activities are one of the leading causes of nitrous oxide (N2O) around the world (Nelson, 2009; Ravishankara *et al.*, 2009). N2O is the third largest greenhouse gas and the primary anthropogenic stratospheric ozone-depleting substance (Turner *et al.*, 2015).
- Water pollution: Nitrate produced by N fertilizer loss enters groundwater through leaching and runoff, causing pollution to drinking water and endangering human health (Reid *et al.*, 2005).
- Eutrophication: Nitrogen oxides from N fertilizer losses lead to the eutrophication of oceans and rivers, which causes algal blooms and fish kills (Hartig *et al.*, 2020).
- Soil acidification: Soil acidification caused by N fertilizer loss affects crop growth and may also allow harmful heavy metals to enter the food chain (Sutton *et al.*, 2013).
- Threats to ecosystems and biodiversity: Nitrogen losses threaten species naturally adapted to low nutrient conditions, putting them at risk of eutrophication (de Vries *et al.*, 2011).

The issues in assessing the benefits and costs of N fertilizer use are explored in Malcolm *et al.* (2022), while a review of the magnitude of the external costs of these pollutants is reported in Tang *et al.* (2023). Here, the discussion is extended to consider the types of government intervention that may be used to reduce this pollution and, hence, the costs to society.

Reducing N fertilizer pollution includes implementing Best Management Practices (BMP), improving farming, irrigation, and drainage techniques, and adopting advanced fertilization technology (Bruce *et al.*, 1996; Sutton *et al.*, 2013). These measures to reduce N fertilizer pollution by reducing the amount of nitrogen fertilizer used may increase farm production costs, reduce farm profits, or increase risk. Farmers lack incentives to reduce N fertilizer use (Gans *et al.*, 2018; Whittaker *et al.*, 2003).

Government intervention is often justified in the implementation of policies to correct market failure. The government can use regulation to force farmers to reduce N fertilizer use or adopt alternative fertilizers or more advanced agricultural practices to reduce N fertilizer pollution (Gans *et al.*, 2018; Whittaker *et al.*, 2003). Regulation is a blunt instrument to achieve a defined level of pollution. Alternatively, the government can adopt a market-based policy, which includes taxes, subsidies, tradeable pollution permits, etc. The government can use taxes to encourage farmers to reduce the amount of N fertilizer use to a level of pollution deemed appropriate, or subsidies can be used to encourage farmers to adopt alternative fertilizers or other agronomic practices to reduce nitrogen pollution. Another option is that the government can set a cap on emissions and use tradeable rights to pollute to limit and adjust the amount of N fertilizer application used. Compared with regulation, market-based policies can usually achieve the goal of reducing pollution at a lower cost (Gans *et al.*, 2018; Von Blottnitz *et al.*, 2006; Whittaker *et al.*, 2003).

Many governments worldwide have made a significant effort to reduce pollution from N fertilizer. For example, the ‘Nitrate Directive’ was introduced by the European Union in 1991 to reduce nitrate leaching by restricting the use of manure and mineral N fertilizers (EU, 1991). In 2015, the Chinese government launched the ‘Zero Growth Action Plan for Fertilizer Use’. The aim was to prevent growth in fertilizer use by 2020, including nitrogen, phosphate, and potash fertilizers, while not reducing food production (Ju *et al.*, 2016).

Although many governments are aware of N fertilizer pollution and the associated external costs, and many have introduced policies involving N pollution in general, few policies explicitly aim to reduce N fertilizer pollution. In addition, there is a lack of assessment of the effectiveness of these policies. It is the aim of this paper to review and summarize the relevant literature relating to these issues.

Two general points can be made about the context of this review. First, even if the correct policy framework is chosen, a lack of data can constrain the efficient application of the policy. To achieve economically efficient levels of N fertilizer pollution, the marginal external cost of the negative externalities arising from using the N is the critical variable. As noted by Tang *et al.* (2023), no studies have reported these marginal negative external costs, so policymakers do not have sufficient information to base efficient intervention decisions. Second, few of the six significant adverse external effects of N fertilizer use mentioned above have been the subject of policy studies. Thus, not all types of pollution have been subject to scrutiny.

Systematic Literature Review

A systematic literature review (SLR) was conducted. Systematic literature reviews enable researchers to identify existing studies, select and evaluate results, analyze and synthesize data, report evidence and draw conclusions (Denyer & Tranfield, 2009). The Durach *et al.* (2017) paradigm of SLR was used. This is based on best practices and the unique attributes of management research (Durach *et al.*, 2017). The steps include defining the research question, determining the required characteristics of the primary study (development of criteria), retrieving samples of potentially relevant literature, selecting pertinent literature, synthesizing the literature, and reporting the results (Durach *et al.*, 2017). Studies that simulated or evaluated the effectiveness of policies to reduce N fertilizer pollution worldwide were the focus. The screening criteria were set to include only literature that met this concern. The search was limited to Chinese and English language literature.

The focus of the SLR was to investigate the research question: What policies have been used to reduce the adverse external effects of nitrogen pollution, and how effective have they been?

Databases and search terms

Three databases were identified to search policies related to N fertilizer pollution: Web of Science, Scopus, and AGRICOLA (EBSCO).

The searched keywords include polic*, regulation*, restriction*, tax*, pollut*, harm*, damage*, "negative effect*", "negative impact*", "negative consequence*", and "nitrogen fertilizer*".

Screening process

A total of 581 results were initially retrieved from the three databases, including Scopus (371), Web of Science (163), and AGRICOLA (EBSCO) (47). After removing 164 duplicates, 417 results remained.

In the first screening of the identified papers, titles and abstracts were reviewed against strict criteria. Only studies related to N fertilizer pollution policy were retained. The 361 studies not explicitly related to N fertilizer pollution policy were deleted, leaving 56 results.

For these 56 possible papers, the full text was reviewed against further criteria according to the aims of the study. Four results without full text were removed, leaving 52 results. Of these, 33 studies did not evaluate the effectiveness of policies used to reduce N fertilizer pollution or researched policies not directly used to reduce N fertilizer pollution. For example, policies used to reduce water pollution are defined, which would include N pollution, but also would include phosphorus pollution and Industrial wastewater pollution. These 33 results were removed. Only studies that evaluated or simulated policies related to N fertilizer pollution were included. Nineteen studies remained.

Synthesizing the results

The 19 final selections were synthesized according to different policy evaluation indicators, policy types, policy effects, or policy effectiveness evaluation results.

Results

From the sizeable initial literature, only 19 studies evaluated the effectiveness of policies related directly to N fertilizer pollution. Although many policies involved N pollution in general, the SLR confirmed that few policies focused on N fertilizer pollution. Many environmental policies involved not only N fertilizer pollution but also other sources of pollution (Westhoek *et al.*, 2004). For example, the European Union's 'Nitrate Directive' limits the amount of nitrates in groundwater, but the sources of these nitrates can include N fertilizers and manure (Bel *et al.*, 2004). It is difficult to assess the effect of these policies alone in reducing the pollution caused by N fertilizers. The 19 relevant studies were sorted and synthesized and are summarized in Table 1.

The 19 studies reviewed included *ex-post* assessments of policies implemented to reduce N fertilizer pollution and *ex-ante* simulation assessments of potential policies to reduce N fertilizer pollution. There were 11 studies in which different policies were simulated and compared. The most studied policy was an N fertilizer tax, with 17 studies evaluating the effect of this policy option. Other policy types evaluated included subsidies, quotas, emissions taxes, N leaching fees, pollution taxes, mandated reduction policy, tradable permits freely issued, and tradable permits auctioned by the government.

The indicators used by these studies to assess the effectiveness of policies include a wide range of measures, such as reduction in the amount of N fertilizer application, reduction in nitrate leaching, producer acceptance, reduction in NO2 emissions, net social benefits, producer costs, and changes in environmental pollution (Andersen *et al.*, 2019; Botterweg *et al.*, 1994; Henseler & Dechow, 2014). However, few of the six major types of negative external effects mentioned in the Introduction have been the subject of policy studies.

Taxes

A tax added to the price of nitrogen fertilizer was the most common policy instrument assessed. The intention of such a policy is that the government could increase the price of N fertilizer through taxes and, therefore, reduce the quantity demanded of N fertilizer, and so achieve the purpose of reducing N fertilizer pollution to a defined level (Bel *et al.*, 2004). There were 17 studies in which the policy effects of taxes, mainly taxes on N fertilizers, but also taxes on nitrate leaching and taxes on pollution, were assessed.

Table 1. Literature reviewed

	References	Study area	Implemented/ Simulated policy	Evaluation Indicators	Type of Policy	Key Effects/ Results
1	(England, 1987)	In the United Kingdom	Ex ante simulation	The amount of N fertilizer application	Tax policy	1. A 100% tax rate results in a 10.6% to 13.9% reduction in the amount of N fertilizer application on farms (4 different crops) 2. Changes in N fertilizer prices lead to changes in crop allocation
2	(Botterweg *et al.*, 1994)	In Europe	Ex ante simulation	Nitrate leaching	Tax policy	When the tax rate reaches 200%, the leaching of nitrate will be reduced, about 7.1% to 25.9% (N fertilizer use is reduced by 25%)
3	(Rayner and Cooper, 1994)	In the United Kingdom	Ex ante simulation	The amount of N fertilizer application	Tax policy	Nitrogen taxes have a limited effect on reducing the amount of N fertilizer application and pollution from N fertilizers (due to low price elasticity)
4	(Giraldez and Fox, 1995)	In Canada	Ex ante simulation	The amount of N fertilizer application	Tax policy	A 55% nitrogen tax could reduce the amount of N fertilizer application from 147kg/ha to 140kg/ha (4.7% reduction)
5	(Bel *et al.*, 2004)	In Europe	Ex-post assessment	The amount of N fertilizer application	Tax policy	N fertilizer prices in Europe have had a weak impact on N fertilizer consumption trends over the past 20 years. 1. When the price elasticity of demand for N fertilizer is low, the tax rate must be 120%-250%. 2. When the price elasticity of demand for N fertilizer is high, the tax rate needs to be 10% to 20%.
6	(Xiang *et al.*, 2007)	Dongting Lake area in China	Ex ante simulation	Environmental pollution	Tax policy	Setting the marginal cost as a tax rate in China's Dongting Lake area will reduce the national environmental loss by ¥70 million and increase the net social benefit

7	(Zhang *et al.*, 2012)	In Jiang Su Province in China	Case study survey	Producer acceptance	Subsidy policy (subsidies for losses caused by reducing N fertilizer use)	68.3% of producers are willing to accept government subsidies and reduce N fertilizer use to the optimal ecological and economic nitrogen application rate
8	(Henseler and Dechow, 2014)	In Germany	Ex ante simulation	N2O emissions	Tax policy	With a (150). % tax on N fertilizer prices, nitrogen emissions are only reduced by 12-13%
9	(Taylor, 1975)	In Illinois, in the United States	Ex ante simulation	The amount of N fertilizer application	1. Tax policy 2. Rights policy	1. A 12% tax rate or 395.4 million pounds of fertilizer rights could reduce the amount of N fertilizers application in corn and wheat by about 77% 2. Both policies have the same net impact on production and the same policy effect
10	(Choi and Feinerman, 1995)	In the United States	Ex ante simulation	The amount of N fertilizer application	1. Tax policy 2. Quota	1. The effectiveness of action-equivalent nitrogen tax policies and quota policies is similar 2. risk-averse farmers use more N fertilizer than risk-neutral farmers. A higher tax is required on risk-averse farmers for them to reduce the same level of nitrogen application as risk-neutral farmers
11	(Feinerman and Falkovitz, 1997)	In the United States	Ex ante simulation	The amount of N fertilizer application	1. Tax on N fertilizers 2. Tax on nitrogen leaching	Taxing N fertilizer is more effective than taxing nitrogen leaching.
12	(Kim *et al.*, 1999)	In the United States	Ex ante simulation	Net social benefit	1. Constant-unit tax 2. Variable-unit tax 3. Pollution tax	The net economic benefit under the variable unit tax policy is the highest to achieve the same pollution reduction effect.
13	(Whittaker *et al.*, 2003)	In the Columbia plateau In the United States	Ex ante simulation	Producer's cost	1. Tax policy 2. Mandated Reduction policy	A 300% tax policy is less costly for farmers than a mandated 25% reduction in N fertilizer usage, has fewer lost profits, and is more efficient in reducing emissions.

14	(Von Blottnitz *et al.*, 2006)	In Europe	Ex ante simulation	Producer's cost	1. Tax Policy 2. Tradable permits that are issued for free 3. Permits that the government auctions	Tradable permits that are issued free are more effective and cause less loss to producers. When the government auctions tradable permits, the public collects these rents and has revenue available to compensate those adversely affected by the pollution.
15	(Bouraoui and Grizzetti, 2014)	In Southern Italy	Ex ante simulation	Net social costs	1. Tax Policy 2. Increase the irrigation water price policy 3. Subsidies for certain agronomic practices that reduce nitrate leaching	1. The least efficient policy to reduce nitrate leaching is irrigation water pricing 2. The most minor cost policy of reducing the same level of negative environmental impact (40% reduction of the initial level of nitrate leaching) is to subsidize the adoption of improved management
16	(Peña-Haro *et al.*, 2010)	In Spain	Ex ante simulation	Net social benefit	1. Tax policy 2. N fertilizer standards policy (Producers are required to apply optimal fertilizer standards)	N fertilizer standards policy is more effective than a nitrogen tax Nitrogen standard policies bring less damage to farmers for the same reduction in nitrate leaching
17	(Pena-Haro *et al.*, 2014)	In Europe	Ex ante simulation	Net social benefit Nitrate leaching	1. Fertilizer price tax policy 2. Water price policy 3. Emission tax policy	The most effective policy is an emissions tax, followed by a fertilizer tax.
18	(Warziniack, 2014)	In the Mississippi-Atchafalaya River basin in the	Ex ante simulation	The size of the hypoxic zone	1. Tax policy on N fertilizers 2. improvements in riparian zones and	A 3% nitrogen tax would reduce the size of the hypoxic zone by 11% but would result in a 2% reduction in maize yields. In comparison, riparian buffers cost less.

		United States			wetlands in agricultural areas	
19	(Mandrini *et al.*, 2022)	In the United States	Ex ante simulation	The amount of N fertilizer application N leaching yield farm profits	1. Higher N prices 2. N leaching fee 3. N balance fee 4. voluntary reduction of N use by farmers (with an incentive compensation equal to the economic loss)	N leaching fee is the most effective policy.

The effectiveness of a N fertilizer tax

The most studied tax policy was a direct tax on the price of N fertilizer, applied to purchases of N fertilizer. It is acknowledged that the demand for N fertilizer is a derived demand, depending not only on the price of N but also on the expected price of the final output, quality specifications of the final output, current and expected weather conditions, type of production system, crop rotation practices, time of year and risk preferences of producers. Given this complexity, it would seem highly unlikely that a one-size-fits-all tax on N fertilizer would be an efficient policy choice.

Unsurprisingly, assessments of the effectiveness of N fertilizer taxes varied widely across the studies reviewed. In some studies, it was pointed out that N fertilizer taxes have limited effects on reducing N fertilizer use and reducing nitrogen pollution because the demand for N fertilizer is price inelastic. In these situations, only a high N fertilizer tax can reduce N fertilizer use and pollution to any significant extent. For example, Rayner and Cooper (1994) modelled the effects of a tax on N fertilizer prices and found that the quantity demanded of fertilizer changed little. The effect of N fertilizer taxes on reducing N fertilizer use and N pollution was limited. A high tax rate would need to be introduced to reduce N fertilizer use significantly.

In addition, Rayner and Cooper (1994) pointed out that N fertilizer taxes cannot achieve significant reductions without significantly increasing farmers' costs and reducing farm profit (Botterweg *et al.*, 1994).

Two other simulation studies that focussed on the change in the amount of N fertilizer used as an indicator to evaluate the effectiveness of an N fertilizer tax reached the same conclusion. One study found that farmer responses to a 100 per cent N fertilizer tax ranged from a 10.6 per cent to 13.9 per cent reduction in total nitrogen use (England, 1987). Another study found that a 55 per cent N fertilizer tax reduced nitrogen use from 147kg/ha to 140kg/ha (a minor 4.7 per cent reduction) (Giraldez & Fox, 1995).

Two studies using NO2 emissions and nitrate leaching as indicators obtained comparable results. In one study, when the simulated tax rate reached 200 per cent, nitrate leaching would be reduced by about 7.1 to 25.9 per cent (Botterweg *et al.*, 1994). Another study concluded that a 150 per cent N fertilizer tax would reduce NO2 emissions by 12-13 per cent (Henseler & Dechow, 2014). Furthermore, Bel's study of the N fertilizer tax policies implemented in Europe in the past 20 years found that the effect of taxes on N fertilizer consumption had been weak. In most countries where a N fertilizer tax had been imposed, N fertilizer consumption trends had not changed significantly (Bel *et al.*, 2004).

In contrast, another study showed that low N fertilizer taxes added to the price of N fertilizer could effectively reduce N fertilizer use. According to Taylor (1975), who looked at N fertilizer use in corn and wheat in Illinois in the United States, a 12 per cent tax rate could reduce N fertilizer use in corn and wheat by about 77 per cent.

The main reason there are different results from the simulation studies reviewed is the different assumptions about the own-price elasticity of N fertilizer demand used in the studies. When the price elasticity of N fertilizer demand is low, the tax rate as a percentage of the fertilizer price needs to be high to reduce demand. By contrast, for producers with a high price elasticity of demand for N fertilizer, the tax rate only needs to be 10-20 per cent to reduce their N fertilizer use effectively (Bel *et al.*, 2004). As mentioned previously, the price elasticity of demand for N fertilizer is affected by many factors, including different crop types, differences in production technology and productivity, the size and structure of farms, etc. (Bel *et al.*, 2004). For example, diversified farms (such as the mixed cropping farms studied by Taylor

(1975)) generally have a higher price elasticity of demand for N fertilizer than specialized farms. As N fertilizer taxes increase, these farmers can use alternative sources of N, such as legume crops, and thus reduce the demand for purchased N fertilizers (England, 1987).

Another study indicated that risk-averse farmers use more N fertilizer than risk-neutral farmers. This meant that to reduce the demand for nitrogen by risk-averse farmers to the same level of nitrogen application as risk-neutral farmers, a higher levy on the fertilizer used by the risk-averse farmers was required (Choi & Feinerman, 1995).

Comparison of N fertilizer taxes with other policies

Although it is difficult to measure the effectiveness of policies taxing N fertilizer use, some studies compared N fertilizer taxes with other policies to identify which one worked best (Choi & Feinerman, 1995; Taylor, 1975; Whittaker *et al.*, 2003). Whittaker *et al.* (2003) compared an N fertilizer tax policy with a mandated reduction policy. They concluded that a 300 per cent tax policy had the same effect in reducing N pollution as a mandated 25 per cent nitrogen reduction policy. However, the N fertilizer tax was less costly to producers and more able to reduce pollution. Even though under the tax policy, every farmer faced the same N fertilizer tax, the profits of some were significantly reduced, while other farmer's profits were little affected. Under the mandatory reduction policy, all farmers were forced to reduce N fertilizer use by the same proportion. However, the financial effects on each farm differed markedly, with some farmers experiencing heavy losses (Whittaker *et al.*, 2003).

In addition, it was shown in some studies that quotas, rights policies, and permit policies were more effective than N fertilizer tax policies and more flexible than a mandated reduction policy (Choi & Feinerman, 1995; Taylor, 1975; Whittaker *et al.*, 2003). As always, when comparing a tax with a tradeable permit method, the permit method defines the quantity of pollution reduction. In contrast, the tax sets the price of pollution, and the quantity has to be discovered (Taylor, 1975). With a tradeable quota, the government can readily adjust the amount of N fertilizer used and the related pollution by adjusting the quota and the number of permits issued. When tradable permits are issued free, producers able to reduce pollution more cheaply than the market price have a windfall gain; when the government auctions permits, the public collects these rents and has revenue available to compensate those adversely affected by the pollution (Von Blottnitz *et al.*, 2006)

Some studies pointed out that N fertilizer taxes that reduced fertilizer use would affect the type of crops that were grown. Producers may shift to crops with lower N fertilizer requirements (England, 1987; Taylor, 1975). For example, in a study conducted in the United States, since corn is an intensive user of nitrogen and soybeans do not require nitrogen fertilization, corn acreage was predicted to decrease and soybean acreage to increase as the simulated N fertilizer tax rates increased (Taylor, 1975)

Other types of taxes

Although the most mentioned tax in the literature review is a fixed rate N fertilizer tax, one study showed that implementing a variable-unit tax on N fertilizers would provide more net economic benefit than a constant-unit tax. In addition, this study pointed out that although the time path of N fertilizer application and the nitrate stock in groundwater would be the same under the constant-unit fertilizer tax and a pollution output tax, the net economic benefit under the constant-unit fertilizer tax policy would be more than that under the pollution tax policy (Kim *et al.*, 1999). Another study had similar conclusions, asserting that nitrate leaching levels were more sensitive to changes in N fertilizer prices (caused by N fertilizer taxes) than to changes in taxes on leached nitrogen (Feinerman & Falkovitz, 1997).

Another study comparing water price policies, N fertilizer taxes, and nitrate leaching taxes had different conclusions. In this study, it was pointed out that although the most effective measure to reduce the total amount of nitrate leaching in the price range was an N fertilizer tax, after considering the private benefits of producers and the loss of social welfare, the nitrate leaching tax was the most effective. At the same time, the study also noted that the same crops may have different cost-effectiveness because of differences in soil and climatic conditions and that taxing N fertilizers may be more cost-effective than taxing nitrate emissions in some cases (Pena-Haro *et al.*, 2014). In addition, several studies have pointed out that a tax on nitrate leaching is more challenging to implement and monitor than a direct tax on N fertilizer use (Feinerman & Falkovitz, 1997; Kim *et al.*, 1999).

Other policy options

Other policies mentioned in these studies as being effective in reducing N fertilizer pollution included subsidies, a leaching fee (a fee on the nitrate leaching from each field), fertilizer standards policy (apply standards to fertilizer use), and investments in riparian buffers (Mandrini *et al.*, 2022; Peña-Haro *et al.*, 2010; Semaan *et al.*, 2007; Warziniack, 2014).

Subsidies could be offered for specific practices that reduce N fertilizer pollution, or farmers could be compensated for the losses caused by reducing N fertilizer use according to the most economical N fertilizer application rate (Semaan *et al.*, 2007; Zhang *et al.*, 2012). By comparing the social costs of three different policies, including raising irrigation water prices, taxing N fertilizers, and subsidies for certain agronomic practices that reduce nitrate leaching, one study indicated that subsidizing agronomic practices to reduce nitrate leaching had lower net social costs than N fertilizer taxes and raising irrigation water prices and achieved the same reduction in nitrate leaching (Semaan *et al.*, 2007).

Another study suggested that regulatory policies on N fertilizer use were more cost-effective than taxing N fertilizer use. However, N fertilizer-regulated usage was more challenging to implement and control than N fertilizer taxes (Peña-Haro *et al.*, 2010). In addition, nitrate leaching fees (charges for additional nitrogen emissions) were also considered to be an effective policy. Charges for additional nitrogen emissions are more cost-effective than N fertilizer taxes but more challenging to monitor and implement than N fertilizer taxes (Mandrini *et al.*, 2022).

Warziniack (2014) argued that although most OECD countries advocate a 'polluter pays' approach in policies addressing N fertilizer pollution, measuring the damage directly caused by the polluter is difficult. Because of the complexity of this economic measurement, the 'polluter pays' principle is rarely put into practice. Therefore, this author proposed, where suitable, investment in pollution reduction infrastructure such as riparian buffers, and suggested that riparian buffers may cost less than a nitrogen tax.

Discussion

How to evaluate the effectiveness of policies

As described above, many policies can be used to reduce N fertilizer pollution, and many have different effects on other indicators such as farm costs or profits. It would be helpful to evaluate the a policy's expected effectiveness before and then actual impacts after implementation to identify which policy type is the most effective (Mandrini *et al.*, 2022; Pena-Haro *et al.*, 2014).

Only one study reported an *ex-post* evaluation from the 19 studies reviewed in this SLR. All others were *ex-ante* simulations of proposed policy settings. In these studies, several different evaluation methods and indicators were used when evaluating the effectiveness of policies (Andersen *et al.*, 2019; Botterweg *et al.*, 1994; Henseler & Dechow, 2014). The indicator used by most studies to assess the effectiveness of the policy was the reduction in the quantity of N fertilizer applied. Since the leading cause of N fertilizer pollution is excessive use, the degree of reduction can be assessed by measuring the reduction of N fertilizer use. Compared to directly evaluating the reduction of pollutants, such as nitrate leaching and NO2 emissions, the reduction of N fertilizer use is more straightforward to measure and evaluate (Feinerman & Falkovitz, 1997).

However, it is not enough to assess the effectiveness of policies only in terms of reducing the amount of N fertilizer applied. Some policies effectively reduce N fertilizer application, but they may cause significant reductions in production and profits or have high implementation costs (Semaan *et al.*, 2007; Zhang *et al.*, 2012). Some studies also assessed the effects of policies on producer costs and profits and producers' acceptance of policies. These factors would also affect the overall net benefits of the policy (Semaan *et al.*, 2007; Von Blottnitz *et al.*, 2006; Zhang *et al.*, 2012).

Thus, many factors warrant assessing when developing and implementing policies. To comprehensively assess the private and social impacts of a policy, some studies used net social benefits as an indicator of policy effectiveness (Mandrini *et al.*, 2022). In assessing the net social benefits of the policy, these studies consider changes in N fertilizer pollution caused by the policy, the impact of the policy on producers, and the cost of implementing the policy. By quantifying the pollution caused by N fertilizer as an external cost, considering the change in costs and benefits of producers as a result of the policy, as well as the cost of policy implementation, the net social benefit of the policy can be evaluated to identify the overall effects of the policy (Pena-Haro *et al.*, 2014; Peña-Haro *et al.*, 2010; Semaan *et al.*, 2007).

Choosing the right policy

N fertilizer taxes

The policy option examined most frequently in the literature reviewed was a direct tax on N fertilizer use. Compared with other policies, the advantages of an N fertilizer tax include: it is easier to implement and costs the government less; it could increase government revenue, and these revenues could be used to offset losses from reduced N fertilizer use (Williamson, 2011); and the increase in N fertilizer prices from the tax can stimulate producers to use more advanced science and technology to reduce N fertilizer use and find alternatives to N fertilizers, such as enhanced efficiency fertilizers, organic fertilizers and biological fertilizers (Xiang *et al.*, 2007). The disadvantages of the N fertilizer tax include: producer responses to taxes can be slow and unpredictable; the amount of the reduction of N fertilizer used under tax policies cannot be predicted when the tax is set (Von Blottnitz *et al.*, 2006); and taxes may lead to a reduction in the area of crops grown with high N requirements. Producers may shift to crops with lower N fertilizer requirements (England, 1987; Taylor, 1975).

It is well-known that the effectiveness of policies is different in different situations (Bel *et al.*, 2004; Pena-Haro *et al.*, 2014), and in the case of an N fertilizer tax, the key difference is the own-price elasticity of demand for N fertilizer. The price elasticity of N fertilizer demand is affected by crop types, crop value, production technology, productivity, the size and structure of farms, farmers' attitude to risk, etc.

To reiterate, when the price elasticity of N fertilizer demand is high, producers are more sensitive to changes in N fertilizer prices. In these cases, a N fertilizer tax is an effective policy to reduce N fertilizer pollution (Taylor, 1975). For producers with high price elasticity of N fertilizer demand, the tax rate only needs to be relatively low to reduce their N fertilizer use and the consequent N fertilizer pollution (Bel *et al.*, 2004). In addition, implementing a variable-unit tax on N fertilizers may be more effective than a constant-unit tax (Kim *et al.*, 1999).

Conversely, when the own-price elasticity of N fertilizer demand is low, the potential to reduce N fertilizer pollution through implementing an N fertilizer tax is limited. With a low own-price elasticity of demand for N fertilizer, only high or exceedingly high N fertilizer taxes achieve the purpose of reducing N fertilizer use and reducing pollution. High taxes increase the cost burden on producers. In this situation, other policy options such as permits, quotas, rights policies, subsidies, leaching fees, and fertilizer standards policies were considered in some studies to be more effective policies than taxes to reduce N fertilizer pollution (Mandrini *et al.*, 2022; Peña-Haro *et al.*, 2010; Semaan *et al.*, 2007).

Knowledge about the own-price elasticity of demand for N fertilizer is usually limited and often dated, especially in Australia. The Industries Assistance Commission (1974) estimated demand functions for nitrogenous fertilizers on six categories of crops. They reported short-run price elasticity estimates ranging from -0.2 (fruit and vines), -0.3 (vegetables), and -0.7 (sugar cane) up to 1.0 (pastures). Penm and Vincent (1987) did a similar study more than a decade later and reported short-run estimates of -0.16 (sugar cane), -0.35 (fruit and vines), -1.18 to -1.40 (wheat) and –2.02 (vegetables). They also reported a long-run elasticity for N fertilizer for pasture of -0.32. Both studies emphasized data issues, especially concerning the N application rate. Given the relative quantities applied to the different sectors, Penm and Vincent (1987, p.73) concluded, 'Variations in fertilizer prices appear to be relatively unimportant in explaining variations in application rate for both phosphatic and nitrogenous fertilizers.' Farquharson *et al.* (2010) reinforced this general conclusion. Using a simulation model calibrated to the Western Australia wheat belt, they estimated arc own-price elasticities of N fertilizer demand off the calculated marginal revenue curve of -0.1 to -0.3. They concluded that 'a policy objective of reducing agricultural N2O emissions by increasing the N price is unlikely to significantly affect farm-level usage of fertilizer' (p. 277). As noted previously, the derived demand for an input such as fertilizer depends on a wide range of factors other than its price.

A similar story is evident in the United States. Carmen (1979) estimated the demand for nitrogen fertilizer in 11 states of the Western United States. He noted that the demand for nitrogen was price elastic (ranging from -1.0 to -1.8) in those States with a focus on extensive grazing industries but inelastic in all other states, especially those with intensive agricultural industries. Carmen (1979) noted that 'the two states with the most inelastic demand, California and Washington, accounted for almost 55 percent of total nitrogen sales in 1977' (p.26). Comparing these results with previous work, Carmen noted that the short-run price elasticity of demand for nitrogen was uniformly inelastic. Again, the older results were confirmed by more recent work. Guha and Wright (2016) concluded that Pigouvian taxes (in this case, to reduce pollution from phosphorus application) 'would not work very well, with a 500 per cent tax cutting on-farm use by just 8 per cent'. Chai *et al.* (2022) noted that a tax on either N as an input or on the quantity of N that leaves the farm had not been applied to N fertilizer in agriculture because the size of the tax needed to achieve pollution reduction was too large. They estimated that a 100 per cent tax would be required for corn in the United States to achieve a 20 per cent reduction in N use. The tax required to achieve a 30 per cent reduction in N would be proportionally larger.

Overall, the demand for N fertilizer seems uniformly price inelastic, especially in the highly N-intensive agricultural sectors. Thus, a tax on N fertilizer use is a poor policy candidate for reducing N pollution.

Other policies to reduce N pollution

Governments could directly limit the amount of N fertilizer used through quota and permit policies (Von Blottnitz *et al.*, 2006).

Policymakers can use subsidies to induce farmers to reduce N fertilizer use directly. Moreover, policymakers can use subsidies to encourage farmers to effectively manage N fertilizer applications according to the best management practices. The government can also encourage farmers to use more advanced, less polluting fertilizers and to adopt more advanced fertilisation techniques through subsidies. In addition, encouraging farmers to improve tillage, irrigation, and drainage techniques through subsidies can also effectively reduce N fertilizer pollution (Bruce *et al.*, 1996; Sutton *et al.*, 2013). Policymakers also need to consider the acceptance of subsidies by producers when developing subsidy policies. Producers' acceptance of subsidies is affected by their education level, environmental awareness, planting experience, etc. (Zhang *et al.*, 2012).

In addition to reducing N fertilizer pollution by implementing innovative policies, reshaping existing direct and indirect subsidies for N fertilizers, and reducing and cancelling subsidies for N fertilizer use, could also reduce N fertilizer pollution (Gazzani, 2021). The main reason for the excessive use of N fertilizers is that some governments use subsidy policies for N fertilizers to promote the use of N fertilizers. Therefore, reducing the subsidies for N fertilizers could also effectively stimulate producers to reduce the amount of N fertilizers and thus reduce N fertilizer pollution (Gazzani, 2021; Xu *et al.*, 2018). Investment in infrastructure to reduce or control some forms of N fertilizer pollution could also effectively reduce the pollution of N fertilizer (Warziniack, 2014).

Conclusion

After summarizing, synthesizing, and comparing the research results of studies in the literature about the effectiveness of N fertilizer pollution policies, it is concluded that compared with other policy options, N fertilizer taxes are easier to implement and have lower implementation costs. Taxes can increase government revenue and encourage farmers to use more advanced agriculture practices. However, producers' responses to N fertilizer taxes are slow and unpredictable, and N fertilizer taxes may lead to changes in farm crop structure. If the price elasticity of demand for N fertilizer by producers is high, producers are more sensitive to changes in N fertilizer prices, and an N fertilizer tax is an effective policy to reduce N fertilizer pollution. However, in the more likely situation, when producers have a low-price elasticity of demand for N fertilizers, taxes are ineffective and permits, quotas, right policies, subsidies, leaching fees, and fertilizer standard policies are more effective policies for reducing N fertilizer pollution.

Other potential ways to reduce N fertilizer pollution worthy of the attention of policy makers include reducing and eliminating some subsidies that are used to encourage N fertilizer use, using subsidies to encourage farmers to reduce N fertilizer use directly, or adopting some agricultural practices that can effectively reduce N fertilizer pollution, and investing in facilities that reduce, prevent, or mitigate pollution.

However, even if the correct policy framework is chosen, a lack of data can constrain the efficient application. To achieve economically efficient levels of N fertilizer pollution, knowledge of the marginal external cost of the negative externalities arising from using the N is necessary. As noted in Tang *et al.* (2023), no studies have reported these marginal negative external costs, so policy makers do not have sufficient information on which to base efficient intervention decisions. Further, few of the six major types of negative external effects mentioned in the Introduction have been the subject of policy studies.

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