Australasian Agribusiness Review
2023, Volume 31, Paper 5
ISSN: 1883-5675

A Critical Review of the External Costs of Nitrogen Fertiliser Use

Xinyue Tang, Garry Griffith and Bill Malcolm[1]

School of Agriculture, Food and Ecosystems Sciences, University of Melbourne.

Abstract

As global population, income and the demand for food rises, increasing quantities of nitrogen fertiliser are used in agricultural activities to enhance the supply of food. While using nitrogen fertiliser increases agricultural production, it also pollutes, which poses a threat to the state of the natural environment and, in some situations, to human health. Although there are many studies on the various types and extent of pollution caused by nitrogen, few studies account for the external costs caused by pollution from nitrogen fertiliser. In this paper a systematic review of the literature was done to collate and synthesise published studies into the external economic losses caused by nitrogen fertiliser pollution. This information should help inform policy makers and stakeholders, to enable improved understanding about the external economic losses caused by nitrogen fertilisers, and to lead to better decisions about reducing pollution from nitrogen used to produce agricultural products. However, none of the reviewed studies report a marginal external cost, so policy makers do not yet have the correct information on which to base efficient intervention decisions.

Keywords: Nitrogen fertiliser, external cost, social cost, externality, pollution.

Introduction

Nitrogen (N) is a key nutrient to plant growth and a means of plants synthesising proteins that people need (Martínez-Dalmau *et al.*, 2021). The N that plants can utilise directly is limited in the natural environment (Robertson and Vitousek, 2009). In 1908, Fritz-Haber combined nitrogen in the air with hydrogen gas to synthesize ammonia and make synthetic nitrogen possible. Subsequently, Carl Bosch improved the catalytic method of high-pressure ammonia synthesis and made possible industrial-scale production of synthetic ammonia, laying the foundation for large-scale industrial production of artificial N fertiliser (Frink *et al.*, 1999). The Haber-Bosch artificial 'nitrogen fixation' process has massively expanded the production of fertilisers such as ammonia, urea, and nitrates which have helped to feed the world population (Erisman *et al.*, 2008).

[1] The authors thank an anonymous referee for helpful comments on an earlier draft.

Global population and incomes have increased markedly in recent decades, the population currently exceeding 7 billion people and expected to reach 10 billion by 2050. The combined effect of rising population and rising incomes means the demand for food globally will increase by 70 per cent in the next 30 years. The emergence of synthetic N fertilisers, particularly since the 1950s, has meant a tenfold increase in the use of N fertilisers since then (FAO, 2022) and more than half the world's crops are grown using synthetic N fertiliser (Ladha *et al.*, 2005). This has greatly increased yields of crops world-wide, enabling the same land to feed more and more people (Frink *et al.*, 1999), tripling global food production over the past 50 years (Janssen, 2006).

While large-scale application of N fertiliser increases crop yield and benefits farmers and consumers, not all N fertiliser that is applied can be absorbed and utilised by plants. A portion is lost to the environment, causing damage to the natural environment, wasting resources and in some situations harming human health (Pannell, 2017). One estimate is that the average nitrogen use efficiency of N fertilisers in the world is less than 50 per cent, which means that the majority of N applied does not go towards producing plant material and harvested yield. Instead, at least half of the N fertiliser applied to agricultural activities is lost to the environment through volatilisation, nitrification, denitrification, leaching, and runoff, which causes pollution to the natural environment and negative effects on human beings (Billen *et al.*, 2013; Ladha *et al.*, 2005). Nitrogen pollution is getting worse and both atmospheric and river nitrogen levels have increased more than 10-fold over the past few decades due to the increased use of synthetic N fertilisers and more intensive crop and pasture production (UN, 2019).

The main negative effects and pollution from the N losses from production include:

- Soil acidification (Sutton *et al.*, 2011).
- Eutrophication. A large amount of nitrogen oxides from N fertiliser loss leads to the eutrophication of oceans and rivers, which causes algal blooms and fish kills (Hartig *et al.*, 2020).
- Air pollution. Ammonium increases the risk of respiratory diseases in humans.
- Groundwater pollution. Nitrates from N fertilisers cause pollution of groundwater, which is harmful to human health (Sutton *et al.*, 2011).
- Global warming. Greenhouse gas (GHG) from N fertilisers makes a substantial contribution to global warming (von Blottnitz *et al.*, 2006).
- Threats to ecosystems and biodiversity (de Vries *et al.*, 2011).

Nitrogen pollution caused by human activities, or negative externalities, brings economic losses, or external costs. Here, the conventional terminology is used that social cost is equal to private cost plus external cost. Large amounts of emissions from agricultural activities are one of the main sources of global N pollution, with nearly 80 per cent of anthropogenic nitrous oxide emissions coming from agriculture. Additionally, 80 per cent of global ammonia (NH3) emissions come from fertiliser use and livestock (UN, 2019).

Governments around the world are increasingly taking steps to try to reduce pollution from N fertilisers. In 1991 the European Union's 'Nitrate Directive' was introduced to reduce nitrate leaching by restricting the application of manure and the application of mineral N fertilisers (EU, 2022). In 2015, a 'circular economy' package of measures was adopted by the European Union aimed to encourage producers to use domestically available biowaste, animal by-products (such as dried manure or manure residues), and other agricultural residues as organic fertilisers. The aim was to reduce the use of synthetic N fertilisers and reduce N pollution (UN, 2019). In 2015 the Chinese government launched the 'Zero Growth Action

Plan for Fertiliser Use' to prevent environmental pollution that was being caused by the rapidly and greatly increasing use of chemical fertilisers (Ju *et al.*, 2016).

Although there are many studies into the negative physical effects caused by nitrogen and the related economic losses, there are fewer studies about the economic losses from the use of N fertiliser (Gourevitch *et al.*, 2014). This is partly because quantifying the size and value of the external costs of N fertilisers is difficult, being a mix of point and non-point pollution and, for some forms of the N pollution, being case-by-case specific. Components of nitrogen fertilisers are dissipated to water, soil, and air in various forms and in turn affect water quality, soil quality, air quality, and climate change. These effects occur on widely differing spatial and temporal scales (Erisman *et al.*, 2013). Further, pollution from N fertilisers can be associated with other sources of pollution, making it difficult to assess the polluting effect individually (Sutton *et al.*, 2011). Regardless, understanding the nature and extent of the external effects and the associated costs of pollution from N fertilisers by reviewing and summarising relevant studies can provide valuable information. Analysing and evaluating the external costs of N fertiliser can help governments and farmers make better decisions about using N in agriculture and about dealing with the consequences that ensue (Keeler *et al.*, 2016).

Initial Literature Review

Nitrogen fertiliser

Nitrogen is an essential nutrient for the growth and survival of plants, animals, and humans. It is a key component of chlorophyll, amino acids, and nucleic acids in plants (Reuter & Robinson, 1997). In addition, nitrogen is 16 per cent of the composition of protein, a key requirement for animal and human survival and growth and which must be obtained from plants, directly or indirectly (Frink *et al.*, 1999).

In the natural environment, biologically available nitrogen is limited and this constrains plant growth and crop yield. Therefore, it is a common practice to increase the nitrogen content in soil by applying N fertiliser to maintain and improve crop yields. On the one hand, N fertiliser can increase crop yield per unit of land area, produce more food, and bring more income to farmers. In the middle of the last century, as a result of the emergence of new technologies and the relatively low cost of N fertiliser compared with its benefits, farmers began to use N fertiliser regularly and in large quantities. Globally, N fertiliser consumption increased from 10 million tonnes in 1961 (FAO, 2021) to 111.6 million tonnes in 2022 (FAO, 2022). Over the past few decades, global food production has increased substantially and global hunger has decreased, at least partly from the widespread production and application of N fertilisers. Food and fibre consumers have also benefitted from lower prices brought about by the increased output.

Global population growth is mainly sustained by the application of N fertilisers to increase food production (Swarbreck *et al.*, 2019). More than half of the world's population is fed by crops grown with synthetic N fertilisers (Ladha *et al.,* 2005). Although the use of N fertilisers has greatly alleviated global hunger, nearly 1 billion people are still undernourished (Chen *et al.*, 2018). In addition, according to projections, the world's population is expected to reach 9.8 billion by 2050 (UN, 2017). To feed the growing global population, an additional 50-70 per cent of cereal grains production will be required (Ladha *et al.*, 2005). Global food demand will expand with growing population and higher incomes and so the demand for N fertiliser will also expand (FAO, 2012).

Nitrogen use efficiency (NUE)

As noted above, the use of N fertiliser that is lost from production is a waste of resources from productive uses and causes external costs through environmental pollution (Foley *et al.*, 2011; Pannell, 2017; Xu *et al.*, 2012). Further, the principle of diminishing marginal returns to biological processes means that eventually using more N fertiliser does not add to yield (Pannell, 2017). As N fertiliser use increases, the increase in yield due to the additional N fertiliser gradually decreases and eventually flattens out. Additionally, in some situations, excessive fertilisation rates may lead to reduced crop yields. In a study conducted in the Mississippi River Basin of the United States, when N fertiliser use increased by 30 per cent across the watershed, the average yield of corn increased by only 4 per cent, but the loss of dissolved inorganic nitrogen (DIN) to the environment increased by an average of 53 per cent. Conversely, when N fertiliser use across the watershed decreased by 30 per cent, the average yield of corn decreased by only 10 per cent, but the loss of DIN to the environment decreased by an average of 37 per cent (Donner & Kucharik, 2003).

Many factors contribute to the overuse of N fertilisers. Policies implemented by some developed and developing countries to protect farmers or to encourage agricultural development can encourage the use of nitrogen beyond any economic private and social optimum (Gazzani, 2021; Xu *et al.*, 2018; Zhang *et al.*, 2017). For example, in Western Europe and the United States, policies that subsidise and raise the prices received for agricultural products above world prices, or policies to protect farmers from competition from cheaper imports, all encourage the use of more nitrogen fertiliser than would otherwise be the case. As another example, in India advice to wheat farmers recommends that farmers apply a fixed amount of N fertiliser at specific stages regardless of temporal and spatial variations in N availability in the soil. This approach results in a low percentage of N fertilisers being used by crops and losses of large amounts of unused N into the environment. Using too much N fertiliser is also related to farmers' pursuit of profit maximisation (Swarbreck *et al.*, 2019). Farmers may apply N fertiliser in pursuit of a yield-maximising crop but diminishing marginal returns means some of the N fertiliser is unused and lost to the environment (Rajsic & Weersink, 2008).

Meeting the growing global food demand and maximising the benefits of farmers using N fertiliser, in addition to increasing nitrogen application and expanding land area, means that improving both technical nitrogen use efficiency (NUE, yield per unit of N measured in various ways) and economic nitrogen use efficiency (the profit maximising level) are key (Adjesiwor & Islam, 2016; Bodirsky & Müller, 2014; Swarbreck *et al.*, 2019). Technical NUE is related to nitrogen uptake efficiency (NUpE) and nitrogen utilisation efficiency (NUtE). NUpE refers to the potential of plants to obtain access to nutrients from the soil; while NUtE refers to the ability of plants to extract these nutrients and transform them into grain (McDonald *et al.*, 2015). The NUE is determined by plant yield relative to per unit of nitrogen application (Moll *et al.*, 1982). The NUE affects crop growth, crop yield, profit, the environment and human nutrition (Duncan *et al.*, 2018). Raun and Johnson (1999) estimated a 20 per cent increase in NUE world-wide could save more than $4.7 billion annually.

Considerable effort has been made to improve technical NUE globally, such as improving management strategies for farming systems, improving N application times and methods, use of precision agriculture technology, crop variety screening comparing the responses of different crops to N, and so on (Dawson *et al.*, 2008; Dent & Cocking, 2017; Fageria & Baligar, 2005; Hawkesford, 2017; Subbarao *et al.*, 2012). In modern agricultural systems, globally the technical NUE is less than 50 per cent, meaning over half of all N applied to crops and plants is lost in the environment and causes pollution (Ladha *et al.*, 2005).

Nitrogen fertiliser pollution

As described, low technical NUE and excessive use of N fertilisers lead to environmental pollution and, in the case of emissions of ammonia, endangering human health (Tyagi *et al.*, 2022). Nitrogen is lost to the environment through denitrification, volatilisation, immobilisation, leaching, and runoff (Raun & Johnson, 1999), as defined below.

Denitrification: Nitrate is formed when N fertiliser enters the soil. Nitrates are converted to gaseous nitrogen by denitrification such as nitric oxide (NO), nitrous oxide (N2O), and dinitrogen gas (N2), and then lost to the atmosphere (Johnson *et al*., 2005).

Volatilisation: N fertiliser enters the soil to produce ammonia, which is converted into ammonia gas through volatilisation and then lost to the atmosphere.

Immobilisation: Nitrate (NO3) and ammonia (NH3) in the soil are taken up by microorganisms in the soil, resulting in the loss of N in the soil.

Leaching: Nitrate in the soil can easily move with water in the soil. Nitrate from N fertilisers accumulates in groundwater through leaching during irrigation and rain events, resulting in soil and water pollution (Galloway *et al.*, 2003; Johnson *et al*., 2005). Leaching of NO3 can be significant when N fertilisation exceeds that required for the maximum yield of cereal crops (Olson & Swallow, 1984; Raun & Johnson, 1995).

Runoff: According to several studies, N loss through runoff is 1-13 per cent of total fertiliser application (Blevins *et al.*, 1996; Chichester & Richardson, 1992).

The N compounds produced through the processes described above can affect adversely water quality, air quality, greenhouse gas balance, the ecosystem and biodiversity, and soil quality (Sutton *et al.*, 2019; Sutton *et al.*, 2011).

Air pollution and greenhouse gas

When NH3 and nitrogen oxides (a mixture of NO and N20) are released into the lower atmosphere, the formation of fine particulate matter and photochemical smog adversely affects human health. In addition, N20 is an irritant gas, which can cause serious damage to the lungs after being inhaled by the human body (Sutton *et al.*, 2013). Indoor high concentrations of N20 can induce various respiratory diseases. Sustained low levels of NO2 can lead to health problems such as cough, headache, loss of appetite, decreased breathing efficiency, etc. (World Health Organization, 2003). In addition, nitrogen oxides are one of the important substances for the formation of tropospheric ozone (O3) and have indirect effects on human health. Human exposure to O3 may trigger or exacerbate cough, asthma, decreased lung function, and chronic respiratory diseases. The particulate matter and N20 formed by nitrogen oxides and NH3 emissions will cause air pollution, which in sufficient quantities endangers human health and reduces the life of some people (Sutton *et al.*, 2013). The World Health Organization indicates that as ozone levels in the environment increase, mortality and respiratory morbidity increase significantly (Amann, 2008). At the same time, tropospheric O3 also contributes to the loss of agricultural crop productivity (Amann, 2008; von Mutius, 2000). Furthermore, aerosol particulate matter formed from NO3 and NH3 can also adversely affect air quality and human health (World Health Organization, 2006)

Fertiliser used in agricultural activities is one of the main causes of N20 emissions into the atmosphere (Nelson, 2009; Ravishankara *et al.*, 2009). According to estimates by the Intergovernmental Panel on

Climate Change, the average amount of N2O emitted by N fertiliser globally is around 0.9 per cent of the N application (Stehfest and Bouwman, 2006). The concentration of N20 in the atmosphere has increased linearly at a rate of about 0.26 per cent per year over the past few decades (Solomon *et al.*, 2007). The main source of N2O is microbial production through nitrification and denitrification, which is stimulated by synthetic N fertilisers, nitrogen fixation by crops, and manure from expanded livestock production (Mosier *et al.*, 1998).

The use of synthetic fertilisers will increase with the increase in human population, per capita meat consumption, and crop-based biofuel production, which will lead to an accelerated growth rate of N2O in the atmosphere (Davidson, 2012). It is considered that N2O is the third largest greenhouse gas in the world and the main anthropogenic stratospheric ozone-depleting substance (Turner *et al.*, 2015). If N2O emissions are not controlled, they will become the most important ozone-depleting substance in the 21st century (Ravishankara *et al.*, 2009).

Water pollution and eutrophication

Nitrates produced by N fertilisers enter groundwater through leaching and runoff, causing serious groundwater pollution, resulting in impure drinking water, and ultimately endangering human health (Reid *et al.*, 2005). Numerous studies have shown that nitrate-contaminated groundwater or vegetables with high nitrate content may cause thyroid cancer, high blood pressure, stomach cancer, neural tube defects, methemoglobinemia ('blue baby' syndrome) in infants, and other diseases in humans (Bahadoran *et al.*, 2016; Powlson *et al.*, 2008; Ward, 2009; Zaldívar & Robinson, 1973). According to the United States Environmental Protection Agency's (EPA's) national water quality inventory report, agriculture is considered the largest contributor to non-point source pollution of groundwater in the United States (USEPA, 1995).

Of the large amounts of synthetic N fertilisers applied to the land, some of the nitrogen compounds are flushed into streams through runoff and eventually into coastal waters, causing eutrophication effects on marine and freshwater systems, causing algal blooms. Algal blooms in aquatic ecosystems produce harmful toxins and deplete large amounts of dissolved oxygen in the water, ultimately leading to fish kills (Vadeboncoeur *et al.*, 2003). It is estimated that 80 per cent of large marine ecosystems are affected by severe eutrophication of coastal waters (Diaz & Rosenberg, 2008; Selman *et al.*, 2008).

Further, the increase of N2O in aquatic ecosystems can lead to the expansion of dead zones (Reid *et al.*, 2005). Over the past few decades, due to increased N2O levels in coastal water, waters that are anoxic (completely devoid of oxygen) or hypoxic (oxygen concentrations below 2 to 3 milligrams per litre), have increased and formed dead zones (Diaz & Rosenberg, 1995).

Soil pollution

Excessive N fertiliser applied to the soil can lead to negative effects and chain reactions. Over-fertilisation can lead to soil acidification and the associated release of free aluminium and heavy metals from soil solutions (Sutton *et al.*, 2013). Soil acidification may reduce crop yield and quality as well as lead to an increase in the absorption of harmful heavy metals by plants, which will eventually lead to the entry of these harmful heavy metals into the food chain and endanger human health (Renkou *et al.*, 2018). Severe soil acidification has occurred in China after heavy N applications (Guo *et al.*, 2010). As well, NH3 and NH4+ from N fertiliser affects the decomposition and mineralisation of organic matter in the soil, affecting the quality of soil organic matter (Sutton *et al.*, 2013). Some studies have pointed out the presence of heavy metal impurities in N fertilisers. For example, large amounts of nickel, lead, and cadmium is present in urea (the most commonly used N fertiliser). These effects on soil are largely a private cost. However, when a large amount of urea is used in agricultural activities, the heavy metal impurities from urea may remain in the surface and groundwater through runoff and leaching, causing a negative externality beyond the private effects (Benson *et al.*, 2014; Schroeder & Balassa, 1963).

Ecosystems and biodiversity

Excess N in the natural environment threatens ecosystems and biodiversity. Excessive nutrients threaten species that are naturally adapted to low-nutrient conditions, putting them at risk of eutrophication. Extensive use of N fertilisers in agricultural activities results in a large number of N compounds entering the original pristine ecosystem that contains sufficient nutrients for plant growth. Long-term deposition of N compounds results in the replacement of species in ecosystems with low or moderate nutrient requirements, and in pH-neutral habitats, by more nitrogen-compatible or acid-tolerant plants (de Vries *et al.*, 2011). In addition, in the vicinity of intensive agricultural production activities, NH3 and NOx emissions can cause extreme foliar damage, especially to lower plants (Sutton *et al.*, 2013).

The external cost of excessive N fertiliser use

As detailed above, the pollution of air, water, and soil caused by excessive N fertiliser use is, in a range of situations, a cause of significant costs to human health and the environment. The pollutants are negative externalities affecting a third party external to the productive transaction, such as in farming activity. The economic costs are the costs of a negative externality. The farmers and others causing the pollution do not pay to compensate those who are negatively affected by the pollution - the external costs they are causing: the markets for fertilisers and the products produced from their application do not include these additional costs. There is market failure. The net benefit to society of the use of N fertiliser is reduced by the uncounted external cost (Gans *et al.*, 2018). These costs are the economic losses arising from air pollution, drinking water pollution, climate warming, eutrophication, etc. as detailed above (Sutton *et al.*, 2019; Sutton *et al.*, 2011).

Quantifying the external cost of N fertilisers is challenging because N from fertilisers is lost in various forms to water, soil, and air. These loss pathways are related to water quality, soil quality, air quality, climate change, etc., and they occur on a case by case basis on different spatial and temporal scales (Erisman *et al.*, 2013). Assessing the negative effects of N fertilisers requires tracking different forms of N across cases, space and time to the end-point where people are affected. Multiple groups of spatially and temporally dispersed people suffer from N-related negative effects and they often respond differently to these effects depending on their preferences and social vulnerability (Lewandowski *et al.*, 2008). In addition, pollution caused by N fertilisers is often associated with other sources of pollution. It is difficult to evaluate them separately.

Some studies have evaluated the external cost of N pollution in total. One study indicated that the total external cost of N from all sources in the United States could exceed $210 billion per year (Sobota *et al.*, 2015). Another study pointed to the total external cost of N in Europe being more than €320 billion/per year (or $US 352 billion at 2015 average exchange rates). The sources of these external costs include not only N fertilisers but also industrial pollutants, other human activities, and pollution from other agricultural activities (Sutton *et al.*, 2011). Integrating the external costs of multiple negative effects from N fertiliser into a single cost metric is not possible because of the diversity of N loss pathways, the mix of point and non-point sources and the spatially and temporally disparate end-points at which damage occurs (Gourevitch *et al.*, 2018). It is still useful though, in situations possible and to the extent possible, to assess the external costs of pollution or negative effects from N fertilisers in particular cases and regions to help inform government and producer decisions (Keeler *et al.*, 2016).

As these external costs of N are typically not included in market prices, the people causing the pollution and therefore generating the external costs lack any incentive to reduce the pollution or minimise the external costs. Furthermore, the external costs are the result of activities that generate economic benefits for farmers, which means that reducing the pollutant emissions and negative impacts of N fertilisers will usual come at a price (Pannell, 2017). Therefore, when external costs cause the allocation of market resources to be ineffective and social benefits are not maximised, governments have a role in developing and implementing policies to improve the allocation of resources, internalise the externalities of N fertilisers and reduce the negative effects from N fertiliser, all with the aim of improving social net benefit of the activities in question. (Gans *et al.*, 2018; Pannell, 2017). These points are taken up later in the Discussion section.

Ways to reduce N fertiliser pollution

Reduced N fertiliser pollution can be achieved in part by improving agricultural practices. Some means and programs to do this include:

- Implementing Best Management Practices (BMP). The '4R Nutrient Management Stewardship' approach means the right fertiliser, the right amount, the right application time, and the right placement method. Soil/plant testing can be used to determine nitrogen needs and N fertilisers can be applied more precisely to reduce emissions, taking into account the available nutrients in the soil, animal manure, crop residues, and waste (Sutton *et al.*, 2013) and combining animal and crop production for manure reuse (Bruce *et al.*, 1996).
- Choosing the right crop variety, planting it in the right crop rotation at the right spacing and time (Sutton *et al.*, 2013).
- Minimising fallow periods, optimising split fertilisation schedules, and reducing soil and water requirements (Bruce *et al.*, 1996).
- Improving farming, irrigation, and drainage techniques (Sutton *et al.*, 2013).
- Adopting advanced fertilisation technology such as controlled-release fertilisers, placing fertilisers below ground surface, foliar application of fertilisers, using nitrification inhibitors, matching fertiliser type to seasonal precipitation, improving plant use of N, etc. (Bruce *et al.*, 1996).

Still, farmers have no economic incentive to adopt some of the above-mentioned measures to improve agricultural practices if the extent of their losses of N is not known or if it costs them to reduce N losses. Governments have a role in fixing failures of markets and can use public policy to achieve improved outcomes.

Governments have a range of policy options. They can impose regulations where farmers in particular situations are required to reduce N fertiliser applications to predefined limits or to adopt alternative fertilisers and more advanced agricultural practices to reduce N fertiliser pollution (Gans *et al.*, 2018; Whittaker *et al.*, 2003).

Alternatively, governments may use market-based policy, which includes introducing taxes, subsidies or tradeable pollution permits to provide the economic incentives to farmers to reduce the amount of N fertiliser use or to encourage farmers to adopt alternative fertilisers or other agronomic practices to reduce nitrogen pollution. Governments can internalise the external costs of N fertilisers with such policies (Gans *et al.*, 2018; Von Blottnitz *et al.*, 2006; Whittaker *et al.*, 2003).

Systematic Literature Review

A systematic literature review (SLR) was undertaken to review and summarise the literature related to the external costs arising from the use of nitrogen fertiliser. Studies related to the external costs of N fertilisers were retrieved, screened, selected, analysed, and synthesised.

The SLR is a specific method used across multiple disciplines. This method can be used to identify and integrate existing studies, to select and evaluate their results, to analyse and synthesise data, and to report the evidence that supports reasonably clear conclusions with minimal bias (Denyer & Tranfield, 2009).

A particular version of SLR was adopted in this research which is based on both best practice and the unique attributes of doing management research (Durach *et al.*, 2017). This paradigm of SLR involves exploring existing studies, paying attention to theoretical boundaries, units of analysis, sources of data, study contexts, and definitions and the operationalisation of constructs, as well as research methods. The specific steps are detailed in the following.

Defining the research question and developing criteria

The research question is 'What is the external cost of pollution (or negative economic impact) from the application of N fertilisers in agricultural production systems?' Studies, reports, data, etc. on the external cost of N, the broader concept of social cost, and externality of N fertilisers around the world is the main concern. The screening criteria were set to include only literature that is highly related to external costs, social costs, or externalities caused by N fertilisers. The language range of search results was limited to Chinese and English.

Databases and search terms

From a comparison of multiple databases, three databases that have the most relevant results were identified, including Web of Science, Scopus, and AGRICOLA (EBSCO).

The searched keywords include "external* cost*", "social cost*", externalit*, “damage* cost*”, "nitrogen fertiliser*".

Screening process

The initial search produced 85 results, including Scopus (48), Web of Science (25), and AGRICOLA (EBSCO) (12). After removing 32 duplicates, there were 53 results left.

In the first screening, titles and abstracts were reviewed against strict criteria. Results unrelated to studies on the externalities of N fertiliser or external costs of N fertiliser or social costs of N fertiliser or damage cost of N fertiliser were removed (29), leaving 24 results.

In the second screening, the full text was reviewed against more stringent criteria according to the aims of the study. Results that were not highly relevant to the externalities and external cost of N fertilisers (11) were deleted. There were 13 results remaining.

Synthesizing the results

The final results are synthesised according to the different study methods of N fertiliser externalities, the different areas of the study, the different types of pollution, the different negative impacts, whether the external cost is directly estimated, and the results of the evaluated analysis.

Results

The 13 studies that were found that are specifically relevant to the external cost of N fertiliser as defined above were sorted and synthesised and are summarised in Table 1.

These 13 studies assessed the external cost of N fertilisers used in different crops and different agricultural activities in different regions by employing both quantitative and qualitative economic methods. The regions studied include China, Europe, Italy, Israel, the United Kingdom, and the United States (Fishman *et al.*, 2009; Nkonya & Featherstone, 2000; Semaan *et al.*, 2007; Soulsby *et al.*, 2002; Von Blottnitz *et al.*, 2006; Xiang, Zhou, Jiang, *et al.*, 2007). Their research scope includes horticulture and livestock (van Grinsven *et al.*, 2015). In addition, some both studied the externalities generated by N fertilisers in the process of use and the externalities generated during the N fertiliser production process (Soulsby *et al.*, 2002; Von Blottnitz *et al.*, 2006).

The main pollution types related to N fertiliser that these studies focus on include nitrate leaching and run off, greenhouse gas (GHG) emissions, small particulate matter (PM2.5) formation, NH3, and other N2O emissions. Nitrate leaching and N2O emissions are the most studied. The negative effects of N fertilisers they studied include global warming, water pollution, eutrophication, land acidification, and the negative impact on human health, on the ecological environment, and on tourism. The negative externalities associated with groundwater pollution (9 papers) and global warming (6 papers) are the most frequently studied (Fishman *et al.*, 2009; Nkonya & Featherstone, 2000; Semaan *et al.*, 2007; Soulsby *et al.*, 2002; Von Blottnitz *et al.*, 2006; Xiang, Zhou, Jiang, *et al.*, 2007).

The external costs of N fertiliser

As shown in Table 1, there are 10 papers in which estimates were made of the external costs caused by the negative effects of pollution from N fertilisers. All of these estimates were either total external costs (typically aggregated over the study region) or average external cost per unit of input such as per hectare of land or per kilogram of N. None of the studies reported estimates of marginal external costs, the key measure required for efficient policy design and intervention.

The estimated average external costs of N fertilisers vary because of the differences in agricultural activities, regions, and types of N fertiliser pollution studied in the different analyses (Soulsby *et al.*, 2002; Von Blottnitz *et al.*, 2006; Xiang, Zhou, Jiang, *et al.*, 2007). For example, when Von Blottnitz assessed the external cost of N fertiliser in the United Kingdom, the greenhouse gas generated during the production of N fertiliser and its raw materials, and its use, were the main focus, and NH3 emissions and nitrate leaching were ignored. The final estimated average external cost of N fertiliser was $0.31/kg N (Von Blottnitz *et al.*, 2006). By contrast, an average external cost of N used in China was estimated to be

Table 1. Summary of research on the external cost of N fertiliser (all cost estimates converted to $US）

Reference	Study Method	Study Area	Types of Pollution	Negative Impacts	Is external cost assessed directly?	External Cost Estimate
(Nkonya & Featherstone, 2000)	Quantitative (A delayed response model)	Irrigated Corn in Western Kansas in the US	Nitrate leaching	Drinking water pollution	No	To keep nitrate concentrations in groundwater below 10 ppm by reducing N fertiliser use: 1. A 13% reduction in N fertiliser use for farmers who apply both nitrogen and phosphorus would result in an 8% reduction in annual returns above variable cost, from $357 to $330 per acre. 2. A 14% reduction in N fertiliser usage for farmers not using phosphorus would result in a 22% reduction in returns above variable costs, from $125 to $98 per acre.
(Soulsby *et al.*, 2002)	Quantitative & Qualitative	In the UK	CO_2 and N_2O from N fertiliser production and transport.	Global warming Negative effects on human health and traffic	Yes	The average external cost is $0.018/kg of N fertiliser use in the UK. *(Original data: (£16/tonne)*
(Von Blottnitz *et al.*, 2006)	Quantitative & Qualitative	In Europe	Greenhouse gases (GHG), NO_x, and NH_4NO_3 from N fertiliser production; N_2O from fertiliser in the soil.	Global warming Eutrophication	Yes	The average external cost of the N fertiliser is estimated at about $0.31 /kg N (compared to the then current market price of about $0.5 /kg N). *(Original data: 0.31 €/kg N and 0.5 €/kg N)*

(Semaan *et al.*, 2007)	Quantitative	A flat farm with an area of 100 hectares in Southern Italy	Nitrate leaching	Water pollution	No	Internalizing the externalities of N fertilisers to reduce nitrate leaching by 40% in 3 ways:resulting in net average social costs: 1. Water tariff policy: \$269/ha[2] 2. Tax on N fertilisers: \$183/ha[3] 3. Management incentives: \$95/ha[4] (*Original data: 269 €/ha, 183 €/ha and € 95/ha)*
(Xiang, Zhou, Jiang, *et al.*, 2007)	Quantitative	The paddy field system of the Dongting Lake area in China	Nitrate leaching N2O emission Eutrophication	Water pollution Fishery output loss Tour business loss Habitation environment loss	Yes	The average external costs are \$ 0.057/ kg N in the Dongting Lake area in China Loss of fishery: \$ 137752.43/ year Loss of drinking water source pollution (water treatment cost): \$ 14050747.86 /year Tourism loss: \$ 1515276.73/ year Loss of habitation environment: \$ 413257.29/year *(Original data: ¥ 0.41, ¥ 1000,000, ¥102,000,000, ¥ 11,000,000, and ¥3000,000)*
(Fishman *et al.*, 2009)	Quantitative (Net social benefit function)	The coastal aquifer in Israel	Nitrate leaching	Groundwater pollution	Yes	The average external cost (drinking water treatment cost) ranges from \$0/year per ha to \$286/year per ha due to different proportions of irrigation water and drinking water allocation

[2] The net social cost for water price policy is 269 €/ha and is calculated as the losses for the farmer, equal to 365 €/ha, minus the gain in revenue for the water agency (96 €/ha).
[3] The net social cost of 183 €/ha is the sum of the losses in the farmer' revenue, 459 €/ha, and the total amount of taxes, 276 €/ ha, that represent a revenue for the society.
[4] To reach about 40% abatement in nitrate leaching level (33 kg-N/ha), the subsidy per hectare is 165 €/ha with a net social cost of 95 €/ha.

(Timmons, 2013)	Quantitative & Qualitative	Switchgrass in western Massachusetts in the US	NH_3, NO, N_2O in the atmosphere; NO_3 in the surface and subsurface water; Nitrate, NO_3 in the groundwater	Global warming Water pollution	Yes	1. The average external cost (treatment) for 67kg N fertiliser application is $75.35/ha. 2. The average external cost (treatment) for 135kg N fertiliser application is: $162.79/ha.
(van Grinsven *et al.*, 2015)	Qualitative	Livestock in the Netherlands and the EU	N pollution	Environmental pollution Negative effects on human health	No	The total external costs of N from agriculture are 0.3–1.9% of GDP in 2008. Internalizing externalities: If the Dutch pig industry, poultry industry, and dairy industry reduce the use of N fertiliser by 40%, the annual total external cost of N fertiliser will be reduced by 40%, or by about $ 0.2-2.2 billion *(Original data: € 0.2-2.2 billion)*
(Xia, Ti, *et al.*, 2016)	Quantitative	staple food (rice, flour, and corn-based fodder) production in China	NH_3 volatilization, NOX emission, N_2O emission, N leaching and runoff, GHG emission	Ecosystems (including soil acidification and eutrophication) Negative effects on human health Global warming	Yes	The total external costs are $44.73 billion /year, with a range of $9.57 –$76.48 billion/year, equivalent to about 1.44% of the GDP of China 1. The average external costs of Ecosystems are $ 4.11/kg N 2. The average external costs of Human health are $ 6.72/kg N 3. The average external costs of global warming are $ 11.26/kg N *(Original data: ¥324.7 billion /year., with a range of ¥69.5–¥555.2 billion/year, Ecosystems: ¥29.8/kg N, Human health: ¥ 48.7/kg N and Climate warming: ¥81.6/kg N)*

(Xia, Xia, *et al.*, 2016)	Quantitative	in the Taihu Lake region in China	NH_3 volatilization N run off N leaching N_2O emission NOx emission	Soil acidification Eutrophication Global warming	Yes	The average external costs (treatments) are $167.23 /ha to $ 330.47 /ha, which approximately accounted for 10.44–13.47% of the farmers' income *(Original data: ¥1214 /ha to ¥2399 /ha)*
(Jesse D. Gourevitch *et al.*, 2018)	Quantitative	corn in Minnesota	Groundwater nitrate (NO_3^-) contamination Small particulate matter (PM2.5) formed from ammonia (NH_3) and N oxides (NOx) Nitrous oxide (N_2O) emissions	Air pollution (PM2.5) Groundwater pollution Negative effects on human health	Yes	The average external cost of N fertiliser: 1. Air pollution (PM2.5): from $ 0.28/kg N - $1.49/kg N 2. Groundwater pollution (willing to pay, treatment cost): from $0.005/kg N - $0.66/kg N 3. Negative effects on human health (the cost of premature mortalities and QALYs-approach): (1) Groundwater pollution: from $0.044/kg N - $1.49 /kg N (2). Air pollution (PM2.5): from $ 0.28/kg N- $1.49/kg N
(Yin *et al.*, 2019)	Quantitative & Qualitative	In China	N_2O emission, NO_3^- leaching, N runoff, NH_3 volatilization	Global warming Water pollution	Yes	The average external cost of applying nitrogen at 173–204 kg N/ha is $142/ha –$218/ha
(Mandrini *et al.*, 2022)	Quantitative	in the US Midwest	Nitrate leaching	Water pollution	Yes	The average external cost of reducing nitrate leaching by 10% at the state level: is $8-10/ha The average external cost of reducing nitrate leaching by 20% at the state level: is $30-37/ha

（Reference exchange rates: GBP/USD: 1/1.15, EUR/USD: 1/1, CNY/USD:1/0.14）

$0.057/kg N. Water pollution, fishery output loss, tour business loss, and habitat environment loss were taken into account, but greenhouse gas emissions were not considered (Xiang, Zhou, Huang, *et al.*, 2007).

The climatic conditions of different regions, the type of crop, the form of nitrogen loss, the application time of N fertilisers, the amount of N fertiliser application, and other factors such as scope of the study affect the pollution counted as being caused by N fertilisers with resulting different total external costs (Fishman *et al.*, 2009; Soulsby *et al.*, 2002; Timmons, 2013; Von Blottnitz *et al.*, 2006; Xiang, Zhou, Jiang, *et al.*, 2007). For example, when nitrogen application in agriculture in the United States was 67kg/ha the average external cost of N fertiliser was estimated to be $75.35/ha. By contrast, when the nitrogen application was 135kg/ha, the average external cost of N fertiliser was estimated to be $162.79/ha. As the amount of N fertiliser applied per unit area increases, the amount of N loss increased, which leads to increases in external costs (Timmons, 2013). Furthermore, by comparing two studies in China, Xia estimated that the average external costs of N fertilisers were between $167.23/ha and $330.47/ha. The average external costs of N fertiliser estimated by Yin were $142/ha – $218/ha. The difference between these two results is a result of the differences in the study areas, types of crops, and N application rates (Xia, Xia, *et al.*, 2016; Yin *et al.*, 2019).

These detailed estimates of the external cost of N fertiliser use reported in Table 1 are sorted and synthesised by net N losses from different types of negative effects, as shown in Table 2.

Table 2. External cost of N fertiliser according to different type of pollution

Number of studies	Negative effect	Average external cost
5	Groundwater pollution	$0.005/kg N to $0.66 / kg N
4	Global warming	$11.26/kg N to $13.98/kg N
2	Negative effects on human health	Negative effects from Air pollution: $ 0.28/kg N to $1.49/kg Negative effects from drinking water pollution: $0.044/kg N to $1.49/ kg N
2	Eutrophication and soil acidification	Eutrophication: about $0.03/kg N (based on the total external cost of eutrophication in the UK per year) Ecosystems loss (including eutrophication and soil acidification): $ 4.11/kg N
2	Negative effects from N fertiliser production *(Taking into account the NOx, NH4NO3 and CO2eq produced during the production of nitrogenous fertilisers and its raw materials, ammonia, and nitric acid)*	$0.16/kg N

Reference exchange rates: GBP/USD: 1/1.15, EUR/USD: 1/1, CNY/USD:1/0.14

External costs due to groundwater pollution

There were seven papers in which the external cost of water pollution caused by N fertiliser application was analysed. In only five papers were specific estimates provided of the external costs of groundwater pollution caused by N fertilisers (Fishman *et al.*, 2009; Gourevitch *et al.*, 2018; Mandrini *et al.*, 2022; Timmons, 2013; Xiang, Zhou, Jiang, *et al.*, 2007).

Groundwater pollution caused by N fertiliser is mainly caused by the leaching and run-off of nitrates (Mandrini *et al.*, 2022; Xia, Ti, *et al.*, 2016). Differences in the spatial location of N fertiliser application, climatic conditions, the form of nitrogen loss, and the application time of N fertiliser meant the groundwater pollution caused by N fertiliser and the degree of pollution are different in each case. In addition, the external costs of water pollution from N fertilisers vary according to different treatments (Fishman *et al.*, 2009; Mandrini *et al.*, 2022). By comparing the models with different assumptions and parameters, Gourevitch *et al*. (2018) provided estimates of the average external costs of water pollution caused by N fertilisers which ranged from $0.005 to $0.66/kg N. The value of people's willingness to pay for nitrate-free drinking water, the value of their willingness to pay for nitrate-safe drinking water, and the cost of the least cost treatment option for contamination comprised a basis for evaluating the external cost of water pollution caused by N fertilisers (Gourevitch *et al.*, 2018). Similar estimates of external costs were also given by Timmons (2013) who found that the average external cost of groundwater pollution caused was about $0.16/kg N. In this study, when the N fertiliser application rate was 67kg/ha, 4.1 per cent of N was lost to groundwater as NO3, causing pollution. In contrast, when the application rate of N fertiliser was 135kg/ha, the loss of N to groundwater as NO3 was 10.8 per cent (Timmons, 2013).

External costs due to global warming

Four papers were focused on the externalities of global warming caused by using N fertilisers. In two papers, the specific external costs of nitrogen fertilisation to global warming were evaluated (Timmons, 2013; Xia, Ti, *et al.*, 2016). The externality arising from N2O emissions from N fertiliser was the primary contributing factor. According to these studies, the average external cost of global warming caused by N fertiliser was between $11.26/kg N and $13.98/kg N (Timmons, 2013; Von Blottnitz *et al.*, 2006; Xia, Ti, *et al.*, 2016).

External costs from other negative effects

Other studies on the externalities caused by N fertilisers included the negative effects on human health, eutrophication, soil acidification, fishery output loss, tour business loss, habitation environment loss, etc (Gourevitch *et al.*, 2018; Von Blottnitz *et al.*, 2006; Xia, Ti, *et al.*, 2016; Xiang, Zhou, Jiang, *et al.*, 2007).

The negative impact of N fertiliser on human health mainly comes from air pollution and drinking water pollution. Sources of these contaminations include NH3 volatilisation, N2O, NOX emission, and N leaching and runoff. Considering premature mortality and the cost of disease treatment, the average external cost to human health caused by N fertilisers from drinking water was estimated to range from $0.044/kg N to $1.49/ kg N. The average external cost to public health caused by N fertilisers from air pollution ranged from $0.28/kg N to $1.49/kg N (Gourevitch *et al.*, 2018; Xia, Ti, *et al.*, 2016).

Von Blottnitz *et al*. (2006) estimated that the average external cost of water eutrophication by N fertilisers in the United Kingdom was approximately $0.03/kg N per year. Again, the specific effects of nitrogen on eutrophication depended on the local nutrient balance and were highly site-dependent (Von Blottnitz *et* *al.*, 2006). Another study from China about soil acidification and water eutrophication caused by N fertilisers concluded that the average external cost of these two types of pollution in aggregate was about $4.11/kg N (Xia, Xia, *et al.*, 2016).

External costs due to N fertiliser production and transportation

Nitrogen fertilisers do not only have negative effects when they are applied; there are also negative impacts on the environment during the production and transportation of N fertilisers. There were two papers that studied the external cost caused by N fertiliser production (Soulsby *et al.*, 2002; Von Blottnitz *et al.*, 2006). Considering the external costs of global warming caused by the greenhouse gases produced during N fertiliser production, as well as the external costs of human health impacts, traffic congestion, and noise during transportation, one study indicated that the average external cost of N fertiliser production and transportation was about $0.006/kg of N fertiliser product used (Soulsby *et al.*, 2002). However, another study that considered the negative effects of NOx, NH4NO3, and CO2eq from N fertiliser production and the production of its raw materials, such as ammonia and nitric acid, indicated that the sum of the average external costs of the whole N fertiliser production process was approximately $0.16/kg N (Von Blottnitz *et al.*, 2006).

Internalising N fertiliser externalities

The literature reviewed above shows that the external costs from the application of N fertilisers in agricultural production systems vary widely. In several of the papers reviewed, ways to reduce these external costs were also canvassed. From the viewpoint of economic efficiency, the first-best way of reducing the negative externality of N fertiliser is by internalising the externality. Producers should be encouraged to reduce N fertiliser application and/or improve current agricultural practices to reduce N fertiliser pollution, and thus reduce N fertiliser external costs (Fishman *et al.*, 2009; Pannell, 2017; van Grinsven *et al.*, 2015). The main ways of internalising N fertiliser externalities mentioned in the reviewed studies include:

- Farmers voluntarily reducing N fertiliser use directly (Nkonya & Featherstone, 2000).
- Increasing N fertiliser prices (Mandrini *et al.*, 2022).
- Taxing N fertilisers.
- Subsidies to encourage certain agronomic practices to reduce N fertiliser use (Semaan *et al.*, 2007).
- Tradeable licenses issued by the government free of charge.
- Tradeable licenses auctioned by the government.
- Limiting the use of N fertilisers by the government (Nkonya & Featherstone, 2000).
- Charging for additional emissions of N such as a leaching fee (Mandrini *et al.*, 2022).

Discussion of these policy options is elaborated in the companion paper (Tang, Griffith and Malcolm, 2023).

Discussion

Synthesising and comparing the selected studies about the external cost of N fertiliser in different situations shows the wide range of estimates of these costs, a range which can be attributed to a number of factors. These include the following.

- The specific cases and spatial and temporal situations of N fertiliser application are different. The climatic conditions, timing and size of rainfall events and existing soil quality, water quality, and natural environment conditions differ in different farm situations, spatial and temporal scales. It leads to differences in the form of N loss, the extent of its negative impact, and the resulting negative effects (Erisman *et al.*, 2013; Gourevitch *et al.*, 2018).

- The agricultural activities involved are different in type and in timing of events during the life of the activities – all of which will differ year-on-year. Different ways of N fertiliser application, N fertiliser application amounts, and types of nitrogen used in different agricultural activities lead to differences in the form of nitrogen loss, the type of pollution, and the degree of pollution (Timmons, 2013; van Grinsven *et al.*, 2015).
- Different studies consider different time ranges. For example, most studies ignore the time lag from when the N fertiliser is applied to when leached nitrate reaches groundwater when assessing the externalities caused by nitrate leaching (Nkonya & Featherstone, 2000).
- Different studies focus on different types of pollution and different negative effects of N fertilisers. For example, some studies only consider the negative externalities caused by the leaching of nitrates (Fishman *et al.*, 2009; Mandrini *et al.*, 2022; Semaan *et al.*, 2007). Some studies also include, where relevant, a loss of subsequent economic activity such as water recreation and tourism attributable to pollution from N fertilisers adversely affecting water quality (Xiang, Zhou, Jiang, *et al.*, 2007).
- The research methods used in different studies also differ. Different evaluation models and parameters adopted by different studies lead to differences in evaluation results. For example: simulated nitrogen application rates are different (Xia, Ti, *et al.*, 2016; Yin *et al.*, 2019); some studies only consider the negative effects of the first transformation of N fertilisers (Gourevitch *et al.*, 2018); and different studies consider different means of pollution treatment, which will also lead to different external costs of N fertilisers (Fishman *et al.*, 2009; Jesse D. Gourevitch *et al.*, 2018).

An implication of this lack of consensus about the magnitude of the estimates of external costs arising from the application of N fertilisers on farms is that there is little point in attempting to implement a common policy intervention mechanism to mitigate all sources of these external costs. In most cases, a case-by-case approach would be more efficient and effective.

By synthesising existing studies on N fertiliser externalities, classification and comparisons were made according to different pollution types and negative impacts. There are only a few studies that estimated the specific external cost of N fertiliser. The external costs of groundwater pollution from N fertiliser were assessed most commonly in these studies, with estimated average external costs associated with groundwater pollution ranging from \$0.005/kg N to \$0.66/kg N (Yin *et al.*, 2019). The second most studied external cost was that of global warming, which caused the highest average external cost, about \$11.26/kg N to \$13.98/kg N (Timmons, 2013; Xia, Ti, *et al.*, 2016). In some papers the external cost associated with human health was investigated. The average external cost caused by negative effects on human health were estimated to be from \$0.28/kg N to \$1.49/kg from air pollution and from \$0.044/kg N to \$1.49/kg N from water pollution (Fishman *et al.*, 2009; Soulsby *et al.*, 2002; Timmons, 2013; Von Blottnitz *et al.*, 2006; Xiang, Zhou, Jiang, *et al.*, 2007).

There are few studies into the external costs of other negative effects, such as eutrophication and soil acidification. Some studies suggested that the external costs caused by eutrophication from N fertiliser were low and could be ignored. With appropriate farming practices, soil acidification can be managed (Von Blottnitz *et al.*, 2006). Many studies ignored some of the negative externalities of N fertilisers because of a lack of relevant data and parameters (Gourevitch *et al.*, 2018). For example, losses from eutrophication were often assessed as a whole, making it is difficult to attribute the role of specific pollutants. This was done because there are so many causes of eutrophication of water bodies, including nitrate deposition after atmospheric discharge of nitrogen oxides, discharges from water plants, improper management of animal manure, nitrate sewage from farmland, phosphate sewage from farmland, etc. Therefore, when assessing the external cost of water eutrophication, it is difficult to separate out the external cost of N fertiliser (Fishman *et al.*, 2012).

Most studies only considered the direct negative effects of N fertilisers when estimating the externalities, ignoring the wider negative effects of N fertilisers. Such wider effects could include:

- Soil acidification caused by N fertiliser promoting the absorption of harmful heavy metals by plants, which may eventually lead to the entry of these harmful heavy metals into the food chain and ultimately harm human health (Renkou *et al.*, 2018).
- The negative effects of N fertilisers on ecosystems and biodiversity, etc. (de Vries *et al.*, 2011; Diaz & Rosenberg, 1995).

Thus, in general, studies evaluating the negative externalities of N fertilisers have focussed on a specific set of negative effects. Other wider, possibly more significant, negative effects associated with N fertilisers were not accounted for by these studies. The true total external cost of N fertiliser is likely greater than the partial external costs assessed by existing studies.

Given the substantial sizes of the range of external costs that can be attributed to N fertiliser application, even if restricted to those that can be easily measured, attention is necessarily directed to ways of reducing these costs. Some options mentioned in the reviewed literature included technical improvements in production systems, such as enhanced efficiency fertilisers, crop breeding, improved irrigation techniques, changed crop rotations, improved N management, etc. Others rely on policy instruments (Von Blottnitz *et al.*, 2006) such as reducing or restricting the demand and use of N fertilisers by influencing or restricting the decision-making of producers (Pannell, 2017). While a detailed discussion of these policy options is in the companion paper (Tang, Griffith and Malcolm, 2023), two clear policy implications flow directly from the material presented above.

First, the uniqueness of situations from which N pollution emanates, and thus the lack of consensus about the magnitude of the estimates of external costs arising from the application of N fertilisers on farms, as reported in Tables 1 and 2, suggests that attempting to implement common policy intervention mechanisms to mitigate all sources of these external costs is impossible, and thus futile. In most cases, a case-by-case approach would be the only effective option. Only for N2O emissions, where there is both a specified pollution source and a market for the pollutant (in CO2eq), would a broad market-based policy solution have any prospect of being successful.

Second, even if the correct policy framework is chosen, the estimates of external costs reported above do not provide the correct measures to allow an efficient application of that policy framework. The rule for the economically efficient quantity of pollution is where marginal social benefit (the market price of the additional food or fibre produced with the N fertiliser) is equal to the sum of the marginal private costs (the costs of producing the food or fibre products) and the marginal external costs of the negative externalities arising from the use of the N. Marginal external cost is the key unknown here. None of the reviewed studies report a marginal external cost, so policy makers do not have sufficient information on which to base efficient intervention decisions.

Conclusion

Estimates of the many types of external costs of N pollution from N fertiliser use in agriculture have been made for many cases and situations and locations globally. Such estimates tell part of the story, though generalisation is fraught. Further, the true external cost of N fertilisers will be more than the sum of any estimates of a range of sources of N pollution across a wide range of situations because not all sources of N fertiliser-related negative effects or pollution are included in the collected studies.

From the systematic literature review of existing studies reported above, estimates of average external costs of N fertiliser for particular cases warrant summarising:

- The external cost of groundwater pollution: $0.005/kg N to $0.66/kg N;
- The external cost of global warming: $11.26/kg N to $13.98/kg N;
- The external cost of negative effects on human health: $0.28/kg N to $1.49/kg N from air pollution and $0.044/kg N to $1.49/kg N from drinking water pollution;
- The external cost of eutrophication: $0.03/kg N; and
- The external cost of N fertiliser whole production process: $0.16/kg N.

To the extent that these indicative external costs of N fertiliser have wider relevance, policymakers at least have some indication, and a better understanding, of the orders of magnitude of the economic losses resulting from pollution from N fertiliser applications in agricultural systems – giving an idea of the imperative to reduce these costs.

The question then becomes one of least cost ways of changing N fertiliser use to reduce N fertiliser pollution and so reduce the external costs. But, as discussed above, for these policy choices to be made efficiently, measures of marginal external costs are necessary. This is where future research effort would be most productively focussed.

References

Adjesiwor, A.T. & Islam, M.A. (2016). Rising nitrogen fertiliser prices and projected increase in maize ethanol production: the future of forage production and the potential of legumes in forage production systems [Review]. *Grassland Science, 62*(4), 203-212. https://doi.org/10.1111/grs.12130

Amann, M. (2008). *Health risks of ozone from long-range transboundary air pollution*. WHO Regional Office Europe.

Bahadoran, Z., Ghasemi, A., Mirmiran, P., Azizi, F. & Hadaegh, F. (2016). Nitrate-nitrite-nitrosamines exposure and the risk of type 1 diabetes: a review of current data. *World Journal of Diabetes, 7*(18), 433.

Benson, N.U., Anake, W.U. & Etesin, U.M. (2014). Trace metals levels in inorganic fertilisers commercially available in Nigeria. *Journal of Scientific Research & Reports, 3*(4), 610-620.

Billen, G., Garnier, J. & Lassaletta, L. (2013). The nitrogen cascade from agricultural soils to the sea: modelling nitrogen transfers at regional watershed and global scales. *Philosophical Transactions of the Royal Society B: Biological Sciences, 368*(1621), 20130123.

Blevins, D.W., Wilkison, D.H., Kelly, B.P. & Silva, S.R. (1996). Movement of Nitrate Fertiliser to Glacial Till and Runoff from a Claypan Soil. *Journal of Environmental Quality, 25*(3), 584-593. https://doi.org/https://doi.org/10.2134/jeq1996.00472425002500030026x

Bodirsky, B.L. & Müller, C. (2014). Robust relationship between yields and nitrogen inputs indicates three ways to reduce nitrogen pollution [Review]. *Environmental Research Letters, 9*(11), Article 111005. https://doi.org/10.1088/1748-9326/9/11/111005

Bruce, J.P., Lee, H. & Haites, E.F. (1996). *Climate change 1995 : economic and social dimensions of climate change.* Edited by James P. Bruce, Hoesung Lee, Erik F. Haites. Published for the Intergovernmental Panel on Climate Change [by] Cambridge University Press. http://www.loc.gov/catdir/toc/cam021/96025453.html

Chen, Q., Peng, S., Dong, H., Wang, W. & Nie, L. (2018). Optimal nitrogen fertiliser management for direct seeding rice: A review [Review]. *International Journal of Agriculture and Biology, 20*(6), 1382-1390. https://doi.org/10.17957/IJAB/15.0658

Chichester, F.W. & Richardson, C.W. (1992). Sediment and Nutrient Loss from Clay Soils as Affected by Tillage. *Journal of Environmental Quality, 21*(4), 587-590. https://doi.org/https://doi.org/10.2134/jeq1992.00472425002100040010x

Davidson, E.A. (2012). Representative concentration pathways and mitigation scenarios for nitrous oxide. *Environmental Research Letters, 7*(2), 024005.

Dawson, J.C., Huggins, D.R. & Jones, S.S. (2008). Characterizing nitrogen use efficiency in natural and agricultural ecosystems to improve the performance of cereal crops in low-input and organic agricultural systems. *Field Crops Research, 107*(2), 89-101. https://doi.org/https://doi.org/10.1016/j.fcr.2008.01.001

de Vries, W., Erisman, J.W., Spranger, T., Stevens, C.J. & van den Berg, L. (2011). Nitrogen as a threat to European terrestrial biodiversity. *The European nitrogen assessment: sources, effects and policy perspectives*, 436-494.

Dent, D. & Cocking, E. (2017). Establishing symbiotic nitrogen fixation in cereals and other non-legume crops: The Greener Nitrogen Revolution [Review]. *Agriculture and Food Security, 6*(1), Article 7. https://doi.org/10.1186/s40066-016-0084-2

Denyer, D. & Tranfield, D. (2009). Producing a systematic review. In *The Sage handbook of organizational research methods.* (pp. 671-689). Sage Publications Ltd.

Diaz, R.J. & Rosenberg, R. (1995). Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna. *Oceanography and Marine Biology. An annual review, 33*, 245-203.

Donner, S.D. & Kucharik, C.J. (2003). Evaluating the impacts of land management and climate variability on crop production and nitrate export across the Upper Mississippi Basin. *Global Biogeochemical Cycles, 17*(3). https://doi.org/10.1029/2001GB001808

Duncan, E.G., O'Sullivan, C.A., Roper, M.M., Biggs, J.S. & Peoples, M.B. (2018). Influence of co-application of nitrogen with phosphorus, potassium and sulphur on the apparent efficiency of nitrogen fertiliser use, grain yield and protein content of wheat: Review [Review]. *Field Crops Research, 226*, 56-65. https://doi.org/10.1016/j.fcr.2018.07.010

Durach, C.F., Kembro, J. & Wieland, A. (2017). A new paradigm for systematic literature reviews in supply chain management. *Journal of Supply Chain Management, 53*(4), 67-85.

Erisman, J.W., Galloway, J.N., Seitzinger, S., Bleeker, A., Dise, N.B ., Petrescu, A.R., Leach, A.M. & de Vries, W. (2013). Consequences of human modification of the global nitrogen cycle. *Philosophical Transactions of the Royal Society B: Biological Sciences, 368*(1621), 20130116.

Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z. & Winiwarter, W. (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience, 1*(10), 636-639.

EU (2022). https://environment.ec.europa.eu/topics/water/nitrates_en

Fageria, N.K. & Baligar, V.C. (2005). Enhancing Nitrogen Use Efficiency in Crop Plants. In *Advances in Agronomy* (Vol. 88, pp. 97-185). Academic Press. https://doi.org/https://doi.org/10.1016/S0065-2113(05)88004-6

FAO (2012). World Agriculture Towards 2030/2050. [Report]. https://www.fao.org/3/ap106e/ap106e.pdf

FAO (2021). Inorganic fertilisers 1961–2019. [Report]. https://www.fao.org/food-agriculture-statistics/data-release/data-release-detail/en/c/1417377/

FAO (2022). World fertiliser trends and outlook to 2022. [Report]. https://www.fao.org/3/ca6746en/ca6746en.pdf

Fishman, Y., Becker, N. & Shechter, M. (2009). Treatment versus prevention of nitrogen fertiliser pollution: An inter-sectoral externality policy model [Article]. *Natural Resource Modeling, 22*(1), 137-171. https://doi.org/10.1111/j.1939-7445.2008.00032.x

Fishman, Y., Becker, N. & Shechter, M. (2012). The Polluter Pays Principle as a policy tool in an externality model for nitrogen fertiliser pollution [Review]. *Water Policy, 14*(3), 470-489. https://doi.org/10.2166/wp.2011.139

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D. & Zaks, D.P.M. (2011). Solutions for a cultivated planet. *Nature, 478*(7369), 337-342. https://doi.org/10.1038/nature10452

Frink, C.R., Waggoner, P.E. & Ausubel, J.H. (1999). Nitrogen fertiliser: retrospect and prospect. *Proceedings of the National Academy of Sciences, 96*(4), 1175-1180.

Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B. & Cosby, B.J. (2003). The Nitrogen Cascade. *BioScience, 53*(4), 341-356. https://doi.org/10.1641/0006-3568(2003)053[0341:Tnc]2.0.Co;2

Gans, J., King, S., Byford, M. & Mankiw, N.G. (2018). *Principles of Microeconomics: Australia and New Zealand Edition*. Cengage AU.

Gazzani, F. (2021). Rethinking the mineral fertiliser subsidy scheme to promote environmental protection in Italy [Article]. *Outlook on Agriculture, 50*(3), 230-237. https://doi.org/10.1177/00307270211031274

Gourevitch, J., Keeler, B. & Polasky, S. (2014). *Estimating the social costs of nitrogen pollution* https://ui.adsabs.harvard.edu/abs/2014AGUFMGC13D0674G

Gourevitch, J.D., Bonnie, L.K. & Taylor, H.R. (2018). Determining socially optimal rates of nitrogen fertiliser application [Journal Article]. *Agriculture, Ecosystems & Environment, 254*, 292-299. https://doi.org/10.1016/j.agee.2017.12.002

Guo, J.H., Liu, X.J., Zhang, Y., Shen, J., Han, W., Zhang, W., Christie, P., Goulding, K., Vitousek, P. & Zhang, F. (2010). Significant acidification in major Chinese croplands. *Science, 327*(5968), 1008-1010.

Hartig, J. H., Krantzberg, G. & Alsip, P. (2020). Thirty-five years of restoring Great Lakes Areas of Concern: Gradual progress, hopeful future. *Journal of Great Lakes Research, 46*(3), 429-442.

Hawkesford, M.J. (2017). Genetic variation in traits for nitrogen use efficiency in wheat [Review]. *Journal of Experimental Botany, 68*(10), 2627-2632. https://doi.org/10.1093/jxb/erx079

Janssen, B.H. (2006). Agriculture and the nitrogen cycle, Assessing the impact of fertiliser use on food production and the environment. *Geoderma, 134*(1-2), 233-234.

Johnson, C., Albrecht, G., Ketterings, Q., Beckman, J. & Stockin, K. (2005). Nitrogen basics–The Nitrogen Cycle [Fact Sheet 2]. *Agronomy Fact Series*(Ithaca, NY: Cornell University Cooperative Extension.). http://nmsp.cals.cornell.edu/publications/factsheets/factsheet2.pdf

Ju, X., Gu, B., Wu, Y. & Galloway, J.N. (2016). Reducing China's fertiliser use by increasing farm size. *Global Environmental Change, 41*, 26-32.

Keeler, B.L., Gourevitch, J.D., Polasky, S., Isbell, F., Tessum, C.W., Hill, J.D. & Marshall, J.D. (2016). The social costs of nitrogen. *Science Advances, 2*(10), e1600219.

Ladha, J.K., Pathak, H., Krupnik, T.J., Six, J. & van Kessel, C. (2005). Efficiency of fertiliser nitrogen in cereal production: retrospects and prospects. *Advances in Agronomy, 87*, 85-156.

Lewandowski, A.M., Montgomery, B., Rosen, C. & Moncrief, J. (2008). Groundwater nitrate contamination costs: A survey of private well owners. *Journal of Soil and Water Conservation, 63*(3), 153-161.

Mandrini, G., Pittelkow, C.M., Archontoulis, S., Kanter, D. & Martin, N.F. (2022). Exploring Trade-Offs Between Profit, Yield, and the Environmental Footprint of Potential Nitrogen Fertiliser Regulations in the US Midwest. *Frontiers in Plant Science, 13*, Article 852116. https://doi.org/10.3389/fpls.2022.852116

Martínez-Dalmau, J., Berbel, J. & Ordóñez-Fernández, R. (2021). Nitrogen fertilization. A review of the risks associated with the inefficiency of its use and policy responses. *Sustainability, 13*(10), 5625.

McDonald, G., Bovill, W., Taylor, J. & Wheeler, R. (2015). Responses to phosphorus among wheat genotypes. *Crop and Pasture Science, 66*(5), 430-444.

Moll, R., Kamprath, E. & Jackson, W. (1982). Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization 1. *Agronomy Journal, 74*(3), 562-564.

Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S. & Van Cleemput, O. (1998). Closing the global N2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. *Nutrient Cycling in Agroecosystems, 52*(2), 225-248.

Nelson, G.C. (2009). *Agriculture and climate change: an agenda for negotiation in Copenhagen* (Vol. 16). International Food Policy Research Institute, Washington, DC.

Nkonya, E.M. & Featherstone, A.M. (2000). Determining Socially Optimal Nitrogen Application Rates Using a Delayed Response Model: The Case of Irrigated Corn in Western Kansas [Article]. *Journal of Agricultural and Resource Economics, 25*(2), 453-467. https://www.scopus.com/inward/record.uri?eid=2-s2.0-0034365944&partnerID=40&md5=dc99a89cc84fa312bc853fbb107a771f

Olson, R. & Swallow, C.W. (1984). Fate of labeled nitrogen fertiliser applied to winter wheat for five years. *Soil Science Society of America Journal, 48*(3), 583-586.

Pannell, D.J. (2017). Economic perspectives on nitrogen in farming systems: Managing trade-offs between production, risk and the environment [Review]. *Soil Research, 55*(5-6), 473-478. https://doi.org/10.1071/SR16284

Powlson, D.S., Addiscott, T.M., Benjamin, N., Cassman, K.G., de Kok, T.M., van Grinsven, H., L'hirondel, J. L., Avery, A.A. & Van Kessel, C. (2008). When does nitrate become a risk for humans? *Journal of Environmental Quality, 37*(2), 291-295.

Rajsic, P. & Weersink, A. (2008). Do farmers waste fertiliser? A comparison of ex post optimal nitrogen rates and ex ante recommendations by model, site and year. *Agricultural Systems, 97*(1-2), 56-67.

Raun, W.R. & Johnson, G.V. (1995). Soil - plant buffering of inorganic nitrogen in continuous winter wheat. *Agronomy Journal, 87*(5), 827-834.

Raun, W.R. & Johnson, G. V. (1999). Improving nitrogen use efficiency for cereal production [Review]. *Agronomy Journal, 91*(3), 357-363. https://doi.org/10.2134/agronj1999.00021962009100030001x

Ravishankara, A., Daniel, J.S. & Portmann, R.W. (2009). Nitrous oxide (N2O): the dominant ozone-depleting substance emitted in the 21st century. *Science, 326*(5949), 123-125.

Reid, W.V., Mooney, H.A., Cropper, A., Capistrano, D., Carpenter, S.R., Chopra, K., Dasgupta, P., Dietz, T., Duraiappah, A.K. & Hassan, R. (2005). *Ecosystems and human well-being-Synthesis: A report of the Millennium Ecosystem Assessment*. Island Press.

Renkou, X., Jiuyu, L., Shiwei, Z., Minggang, X. & Renfang, S. (2018). Scientific issues and controlling strategies of soil acidification of croplands in China. *Bulletin of Chinese Academy of Sciences (Chinese Version), 33*(2), 160-167.

Reuter, D. & Robinson, J.B. (1997). *Plant analysis: an interpretation manual*. CSIRO Publishing.

Robertson, G.P. & Vitousek, P.M. (2009). Nitrogen in agriculture: balancing the cost of an essential resource. *Annual Review of Environment and Resources, 34*(1), 97-125.

Schroeder, H.A. & Balassa, J.J. (1963). Cadmium: uptake by vegetables from superphosphate in soil. *Science, 140* (3568), 819-820.

Selman, M., Greenhalgh, S., Diaz, R. & Sugg, Z. (2008). Eutrophication and hypoxia in coastal areas: a global assessment of the state of knowledge. *World Resources Institute, 284*, 1-6.

Semaan, J., Flichman, G., Scardigno, A. & Steduto, P. (2007). Analysis of nitrate pollution control policies in the irrigated agriculture of Apulia Region (Southern Italy): A bio-economic modelling approach [Article]. *Agricultural Systems, 94*(2), 357-367. https://doi.org/10.1016/j.agsy.2006.10.003

Sobota, D.J., Compton, J.E., McCrackin, M.L. & Singh, S. (2015). Cost of reactive nitrogen release from human activities to the environment in the United States. *Environmental Research Letters, 10*(2), 025006.

Solomon, S., Qin, D., Manning, M., Averyt, K. & Marquis, M. (2007). *Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC* (Vol. 4). Cambridge university press.

Soulsby, P.G., Hickman, G.A.W. & McMahon, P.L. (2002). Economics of recovering value from recycling treated biosolids to land [Article]. *Journal of the Chartered Institution of Water and Environmental Management, 16*(1), 18-24. https://doi.org/10.1111/j.1747-6593.2002.tb00362.x

Stehfest, E. & Bouwman, L. (2006). N2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. *Nutrient Cycling in Agroecosystems, 74*(3), 207-228.

Subbarao, G., Sahrawat, K.L., Nakahara, K., Ishikawa, T., Kishii, M., Rao, I., Hash, C., George, T., Rao, P.S. & Nardi, P. (2012). Biological nitrification inhibition—a novel strategy to regulate nitrification in agricultural systems. *Advances in Agronomy, 114*, 249-302.

Sutton, M., Raghuram, N., Adhya, T.K., Baron, J., Cox, C., de Vries, W., Hicks, K., Howard, C., Ju, X. & Kanter, D. (2019). The nitrogen fix: from nitrogen cycle pollution to nitrogen circular economy. *Frontiers 2018/19: Emerging Issues of Environmental Concern,* Chapter 4.

Sutton, M.A., Bleeker, A., Howard, C., Erisman, J.W., Abrol, Y.P., Bekunda, M., Datta, A., Davidson, E., Vries, W., Oenema, O. & Zhang, F. S. (2013). Our nutrient world. The challenge to produce more food & energy with less pollution. *Global Overview of Nutrient Management.* Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative.

Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., Van Grinsven, H. & Grizzetti, B. (2011). *The European nitrogen assessment: sources, effects and policy perspectives*. Cambridge University Press.

Swarbreck, S.M., Wang, M., Wang, Y., Kindred, D., Sylvester-Bradley, R., Shi, W., Varinderpal, S., Bentley, A.R. & Griffiths, H. (2019). A Roadmap for Lowering Crop Nitrogen Requirement [Review]. *Trends in Plant Science, 24*(10), 892-904. https://doi.org/10.1016/j.tplants.2019.06.006

Tang, Xinyue, Griffith, Garry and Malcolm, Bill (2023). A critical review of the effectiveness of policies to reduce nitrogen fertilizer pollution globally. *Australasian Agribusiness Review* (submitted).

Timmons, D. (2013). Social cost of biomass energy from switchgrass in western Massachusetts [Article]. *Agricultural and Resource Economics Review, 42*(1), 176-195. https://doi.org/10.1017/S1068280500007681

Turner, P.A., Griffis, T.J., Lee, X., Baker, J.M., Venterea, R.T. & Wood, J.D. (2015). Indirect nitrous oxide emissions from streams within the US Corn Belt scale with stream order. *Proceedings of the National Academy of Sciences, 112*(32), 9839-9843.

Tyagi, J., Ahmad, S. & Malik, M. (2022). Nitrogenous fertilisers: impact on environment sustainability, mitigation strategies, and challenges [Review]. *International Journal of Environmental Science and Technology*. https://doi.org/10.1007/s13762-022-04027-9

UN (2017). World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100. [Report]. https://www.un.org/en/desa/world-population-projected-reach-98-billion-2050-and-112-billion-2100

UN (2019). Frontiers 2018/19: Emerging Issues of Environmental Concern [Report]. https://wedocs.unep.org/20.500.11822/27538.

USEPA (1995). *National water quality inventory: 1994 report to congress* (Vol. 2). US Environmental Protection Agency, Office of Water, Washington, DC.

Vadeboncoeur, Y., Jeppesen, E., Zanden, M.J.V., Schierup, H.H., Christoffersen, K. & Lodge, D.M. (2003). From Greenland to green lakes: cultural eutrophication and the loss of benthic pathways in lakes. *Limnology and Oceanography, 48*(4), 1408-1418.

van Grinsven, H.J.M., Erisman, J.W., de Vries, W. & Westhoek, H. (2015). Potential of extensification of European agriculture for a more sustainable food system, focusing on nitrogen. *Environmental Research Letters, 10*(2), Article 025002. https://doi.org/10.1088/1748-9326/10/2/025002

Von Blottnitz, H., Rabl, A., Boiadjiev, D., Taylor, T. & Arnold, S. (2006). Damage costs of nitrogen fertiliser in Europe and their internalization [Article]. *Journal of Environmental Planning and Management, 49*(3), 413-433. https://doi.org/10.1080/09640560600601587

von Mutius, E. (2000). The environmental predictors of allergic disease. *Journal of Allergy and Clinical Immunology, 105*(1), 9-19.

Ward, M.H. (2009). Too much of a good thing? Nitrate from nitrogen fertilisers and cancer. *Reviews on Environmental Health, 24*(4), 357-363.

Whittaker, G., Färe, R., Srinivasan, R. & Scott, D.W. (2003). Spatial evaluation of alternative nonpoint nutrient regulatory instruments [Article]. *Water Resources Research, 39*(4), WES11-WES19. https://doi.org/10.1029/2001WR001119

WHO (2003). *Health aspects of air pollution with particulate matter, ozone and nitrogen dioxide.* Report on a WHO working group, Bonn, Germany 13-15 January.

WHO (2006). *Air quality guidelines: global update 2005: particulate matter, ozone, nitrogen dioxide, and sulfur dioxide*. World Health Organization.

Xia, L., Ti, C., Li, B., Xia, Y. & Yan, X. (2016). Greenhouse gas emissions and reactive nitrogen releases during the life-cycles of staple food production in China and their mitigation potential [Article]. *Science of the Total Environment, 556*, 116-125. https://doi.org/10.1016/j.scitotenv.2016.02.204

Xia, L., Xia, Y., Ma, S., Wang, J., Wang, S., Zhou, W. & Yan, X. (2016). Greenhouse gas emissions and reactive nitrogen releases from rice production with simultaneous incorporation of wheat straw and nitrogen fertiliser [Article]. *Biogeosciences, 13*(15), 4567-4579. https://doi.org/10.5194/bg-13-4569-2016

Xiang, P.A., Zhou, Y., Huang, H. & Zheng, H. (2007). Discussion on the Green Tax Stimulation Measure of Nitrogen Fertiliser Non-Point Source Pollution Control - Taking the Dongting Lake Area in China as a Case [Article]. *Agricultural Sciences in China, 6*(6), 732-741. https://doi.org/10.1016/S1671-2927(07)60106-0

Xiang, P.A., Zhou, Y., Jiang, J.A., Zheng, H., Yan, H.M. & Huang, H. (2007). External Costs and Optimum Use of Nitrogen Fertiliser Based on the Balance of Economic and Ecological Benefits in the Paddy Field System of the Dongting Lake Area, China [Article]. *Agricultural Sciences in China, 6*(3), 347-354. https://doi.org/10.1016/S1671-2927(07)60055-8

Xu, G., Fan, X. & Miller, A.J. (2012). Plant nitrogen assimilation and use efficiency. *Annual Review of Plant Biology, 63*, 153-182.

Xu, H., Liu, Z., Wang, L., Wan, H., Jing, C., Jiang, J., Wu, J. & Qi, J. (2018). Trade-offs and spatial dependency of rice production and environmental consequences at community level in Southeastern China [Article]. *Environmental Research Letters, 13*(2), Article 024021. https://doi.org/10.1088/1748-9326/aaa135

Yin, Y., Ying, H., Xue, Y., Zheng, H., Zhang, Q. & Cui, Z. (2019). Calculating socially optimal nitrogen (N) fertilization rates for sustainable N management in China [Article]. *Science of the Total Environment, 688*, 1162-1171. https://doi.org/10.1016/j.scitotenv.2019.06.398

Zaldívar, R. & Robinson, H. (1973). Epidemiological investigation on stomach cancer mortality in Chileans: association with nitrate fertiliser. *Zeitschrift für Krebsforschung und Klinische Onkologie, 80*(4), 289-295.

Zhang, D., Shen, J., Zhang, F., Li, Y.E. & Zhang, W. (2017). Carbon footprint of grain production in China. *Scientific Reports, 7*(1), 1-11.