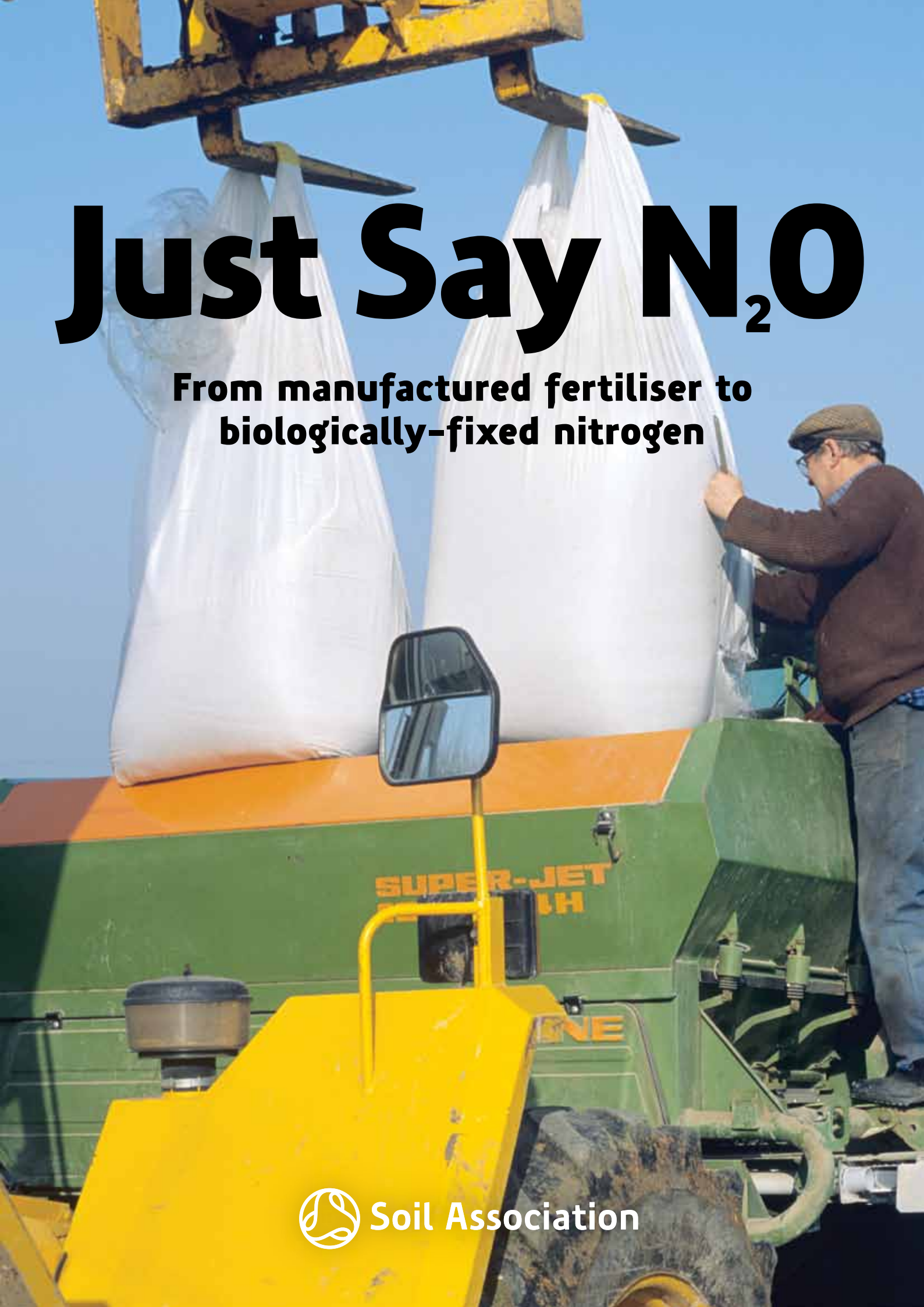


Just Say N_2O

From manufactured fertiliser to biologically-fixed nitrogen

Soil Association

Executive summary

'Too much nitrogen harms the environment and the economy' was the key message of the recent European Nitrogen Assessment which reported a study carried out by 200 scientists investigating the unprecedented changes humans have made to the global nitrogen cycle over the last hundred years.[1] Through industrial processes, the cultivation of crops and the burning of fossil fuels, the supply of *reactive* nitrogen into the global environment has doubled.[2]

The biggest source of reactive nitrogen is from the industrial manufacture of nitrogen fertilisers for agriculture using the Haber-Bosch process.[3] Its introduction to farms around the world during the 20th century has led to a profound transformation of agriculture. Manufactured fertilisers have contributed to the intensification of agriculture, and played a key role in increasing crop yields over the last 50 years, albeit at a decreasing output per tonne of nitrogen applied in many parts of the world.[4]

Our dependency on manufactured nitrogen for our food supply is, however, deeply worrying. The production of manufactured fertilisers is very energy intensive and uses natural gas, a non-renewable fossil fuel that will get more expensive as supplies get scarce, putting an upward pressure on fertiliser and food prices. This poses a long-term threat to food security. Nitrate leaching into water systems is a major problem, whilst the production, transportation and use of manufactured fertiliser contribute to greenhouse gas (GHG) emissions. Of particular concern are emissions of nitrous oxide (N_2O), a powerful GHG, with a global warming potential of 298 times that of carbon dioxide.[5] N_2O makes up 54% of the UK agricultural sector's GHG emissions.[6]

Recent research from the University of Illinois challenges conventional wisdom by indicating that in some circumstances the use of manufactured nitrogen can cause the loss of soil organic matter by stimulating the activity of soil micro-organisms.[7] Where soils are not managed carefully with appropriate levels of organic matter inputs, this can reduce the ability of soils to store carbon, to hold water, as well as to store organic nitrogen and thus lead to higher nitrogen losses to the environment. Further research is needed to see if such results are replicated in other studies, but this report supports the concern that the organic movement has had for decades about the long-term sustainability of a farming system reliant on manufactured nitrogen fertilisers.

Of course, all agricultural systems need a supply of nitrogen to replenish that lost when crops are harvested, and some loss of nitrogen is inevitable. So how should we best deal with the environmental consequences, N_2O emissions and future food insecurity caused by our century-long love affair with manufactured nitrogen?

Biologically-fixed nitrogen in organic systems

In this report we discuss how current policy and potential technological-fixes to deal with the problems caused by manufactured nitrogen are inadequate, or are unlikely to deliver within the time-frame needed. Instead, we show how resolving the problem of our dependence on manufactured nitrogen requires a transformation of our agricultural systems to those that obtain nitrogen from nitrogen-fixing legumes.

We review the current evidence on the extent to which organic systems can meet the double challenge of reducing nitrogen losses and building stores of soil organic nitrogen in order to reduce dependency on

Executive summary

manufactured nitrogen. The use of manufactured nitrogen is not allowed in organic systems, so inputs of nitrogen come from nitrogen fixed by legumes, often clover leys as part of a crop rotation that also controls pest and diseases.

Making the most efficient use of limited nitrogen inputs will become a key driver for agricultural systems in the future. Research has found smaller nitrogen surpluses on organic farms than non-organic, due to the ban on manufactured fertilisers and limited livestock densities. Research published in the journal *Science* found that nutrient input including nitrogen in the organic systems to be 34–51% lower than in non-organic systems, whereas mean crop yield was only 20% lower over a period of 21 years.[8]

Scientific evidence shows that the lower nitrogen inputs in organic farming systems can lead to lower N_2O emissions compared to non-organic farms on an area basis, although research comparing the N_2O emissions from the two farming systems is limited. Most of the existing studies do not include the GHG emissions from producing manufactured nitrogen that is used on non-organic farms. Potential N_2O hotspots on organic farms include the decomposition of manure and the incorporation of green manure crops including legumes.

Reducing nitrogen losses and N_2O emissions

'Biologically-fixed' nitrogen can also cause un-necessary N_2O emissions and pollution if not managed properly, as can animal wastes that return nitrogen to the soil. Therefore, correctly timed farming practices are required to minimise the amount of newly-fixed nitrogen needed as an input in the first place, and prevent nitrogen being lost to the environment.

BEST PRACTICE FOR FARMERS USING LEGUME-BASED SYSTEMS

Measures should be taken to ensure that the release of nitrogen synchronises with demand for nitrogen by crops. These could include:

- Changing the timing of the ploughing of legume leys and the establishment of new crops. Autumn ploughing is problematic as mineralisation occurs before peak nitrogen demand from crops in spring: delaying ploughing to spring avoids this. Winter crops planted in the autumn develop slowly in the autumn with low nitrogen demand.
- Avoiding fields left exposed without vegetation by planting cover crops, or under-sowing leys or winter cover crops into a growing crop before harvest.
- Avoiding applications of animal waste in late summer/early autumn when the risk of leaching is at its highest.

Building soil organic nitrogen

It is argued by some that biologically-fixed and manufactured nitrogen are indistinguishable once in organic form and equally become potential sources for N_2O emissions and other nitrogen losses.[9] However, there is now evidence that farming systems using these different types of nitrogen do function differently in terms of nitrogen retention and loss. In addition to the research from the University of Illinois, research published in the journal *Nature* in 1998 found that the level of nitrogen in soils is not just controlled by the net input of nitrogen,

but that the *type* of nitrogen is also important. On research plots, legume-based systems had a higher retention of nitrogen in the soil in the long-term and less nitrate leaching, than the system using the same quantity of nitrogen from manufactured fertilisers.[10]

More research urgently needed

We outline here the known benefits of the organic system to reducing nitrogen surpluses, nitrate leaching, and N_2O emissions. Nevertheless, it is clear that specific understanding of how nitrogen behaves within legume-based systems is currently limited. Given the imperative to reduce our reliance on manufactured nitrogen and improve the efficiency of nitrogen use, we urge the Government to commission work in a number of specific areas:

- The Government should investigate the likelihood that legume-based organic systems and those using manufactured nitrogen behave differently in terms of nitrogen cycling, retention and loss. There is an urgent need to understand the consequence of this for long-term soil fertility, reducing GHG emissions, storing carbon in soil and reducing our dependence on manufactured fertilisers.
- The Government should fund research that looks in detail at N_2O emissions from organic systems to bring scientific understanding to the same level as will be provided by the Government's 'InvenN_2Ory' project for non-organic farming practices. This would contribute to the 'future-proofing' of the UK GHG Inventory and ensure that emissions from organic systems are represented using accurate emissions factors.
- There is an urgent need for further research into best practice for organic farms and other agro-ecological farming systems on how N_2O emissions and other nitrogen losses can be minimised. Research is also needed into innovative methods already being trialled on organic farms. For example, alternatives to ploughing in legumes such as crops direct-drilled into legumes, the use of perennially-based cropping systems and agroforestry.
- The European Nitrogen Assessment called for a lowering of the human consumption of animal protein as a way of also tackling nitrogen excesses.[11] Research into the impact of nitrogen use and pollution as a consequence of a shift in diets in the UK to lower consumption of meat and dairy products, especially from animals fed on grain rather than grass, should be commissioned to accompany existing evidence of the climate change and health benefits.
- Using clover on grassland to fix new nitrogen, rather than manufactured nitrogen is a practice that can be readily adopted by non-organic farmers. The use of winter cover crops by those growing spring sown crops should also be encouraged. The Government should provide financial incentives to help farmers implement such measures, and these could be included as part of the 'greening' of Pillar 1 of the Common Agriculture Policy.

Introduction

The importance of nitrogen in agriculture

Nitrogen is the element that plants require in greatest amounts and it is used within plant cells to build important compounds such as amino acids for proteins. A nitrogen deficiency rapidly inhibits plant growth. Over 78% of the atmosphere is composed of nitrogen, but in this gaseous form (N_2), it is not usable by plants. Some plants, such as legumes, can 'fix' N_2 from the atmosphere themselves. They do this by forming a symbiotic relationship with nitrogen-fixing bacteria (*Rhizobium* genus) that are found in the soil and form nodules on the roots of the plants. In exchange for fixed nitrogen from the bacteria, the plants provide the bacteria with assimilates (via photosynthesis) and other nutrients. Nitrogen fixing crops are well known as sources of nitrogen for agriculture and legumes are generally used in organic agriculture as a source of nitrogen for the farming system. Other nitrogen-fixing bacteria are free-living in the soil, and can provide small amounts of nitrogen for plants. [12]

Plants that cannot fix their own nitrogen take up nitrogen from the soil through their roots. They can take up small organic nitrogen molecules (e.g. peptides and amino acids), ammonium (NH_4+) and nitrate (NO_3-).[13] Plant available nitrogen is released from decomposing organic matter, that includes animal manures and crop residues returned to the soil, and legume crops that have been ploughed in. Soil organisms break down the organic matter and nutrients, including nitrogen, are released into the soil in a mineral form that plants can use in a process called *mineralisation.* Ammonium is rapidly converted to nitrate by the process of *nitrification*. This reaction produces nitrous oxide (N_2O) as a by-product. Nitrate is soluble and does not bind to soil surfaces, making it prone to being lost from the soil through leaching, causing environmental pollution. Under waterlogged conditions, nitrate can be further transformed to N_2 in a process called *denitrification,* and N_2O is again a by-product.

What is the Haber-Bosch process?

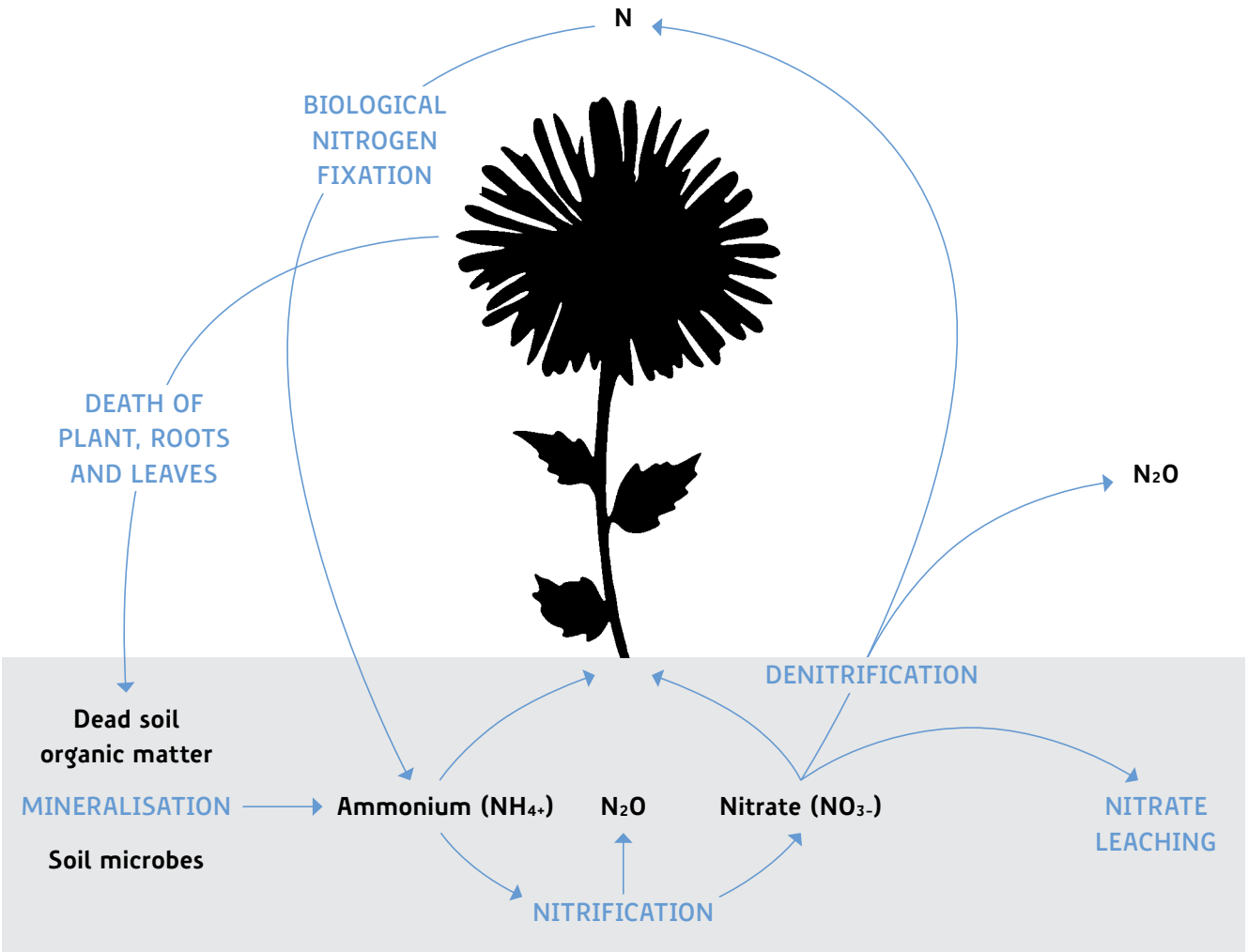
Since the invention of the Haber-Bosch process, that mimics biological fixation, but 'fixes' nitrogen through industrial means, many crops in agricultural systems get nitrogen from the direct application of manufactured nitrogen fertilisers (often containing urea or ammonium nitrate), rather than from organic nitrogen mineralised through biological processes in the soil.

The discovery that ammonia, a chemically reactive, highly usable form of nitrogen could be synthesised by taking nitrogen from the air (N_2) and reacting it with hydrogen in the presence of iron at high pressures and temperatures, was first made by Fritz Haber, who was awarded the Nobel Prize in Chemistry in 1919. The process was developed on an industrial scale by Carl Bosch who was awarded a Nobel Prize in 1931. In his Nobel lecture, Haber claimed his main motivation for making ammonia was for fertiliser to keep up with the growing demand for food, but what he did not mention was his other motivation, to produce ammonia for weapons for the German army in the First World War. Since then, reactive nitrogen produced by the Haber-Bosch process has become a key foundation of global ammunition supplies.[14]

Today, most of the reactive nitrogen produced by industrial processes is used to make ammonia for agricultural fertilisers.[15] In 2008 it was estimated that industrial production in Europe of reactive

nitrogen was 34 million tonnes, of which 75% was for fertilisers and 25% for the chemical industry.[16] This process requires a supply of hydrogen and in around 67% of cases natural gas is the feedstock because it is the energy source with the highest hydrogen content. Manufacturers using coal as a feedstock make up a further 27% of the fuel source, of which 97% are in China. Fuel oil makes up 3%.[17] Water also provides almost half of the hydrogen in the modern commercial process. The chemical reaction to 'fix' nitrogen requires a lot of energy, and it is estimated that approximately 70% of the fossil fuels is used as a source of hydrogen, while the rest is used as fuel.[18]

Simplification of the nitrogen cycle showing major pathways in plant ecosystem



Adpated from Butterbach-Bahl, K & Gunderson, P (2011), 'Nitrogen processes in terrestrial ecosystems', in Sutton (2011), *Summary for Policymakers*

The problems with manufactured nitrogen

The widespread use of manufactured nitrogen in agricultural systems causes problems in its production and in its use.

Making manufactured nitrogen

Energy and hydrogen from fossil fuels

Current manufactured nitrogen fertiliser production is reliant on fossil fuels, mainly natural gas, as a source of hydrogen and as a fuel for the chemical process. Despite a six-fold increase in energy and feedstock efficiencies between 1903 and 2003,[19] growth in the rate of production still means that on a global scale fertiliser production uses approximately 1.2% of the world's energy.[20] On a farm scale, manufactured fertilisers are estimated to account for 68% of on-farm commercial energy use in the Global South, and 40% in the Global North, where more energy is used by farm machinery.[21]

Insecure supply

Natural gas is a finite and depleting fossil fuel, and like oil, at some point in the future its supply will 'peak', if it has not already done so. As Hubert (1956)[22] first highlighted in relation to peak oil, it is not when a resource is completely gone that problems arise, but when the high quality, highly accessible reserves have been depleted. This is the point at which production reaches its maximum (its peak) and afterwards the quality of the remaining reserves is lower, harder to access and thus increasingly expensive to extract. Supply then declines and price rapidly increases. 'Peak gas' is now receiving some political attention in the UK.[23] What this will mean for manufactured nitrogen fertiliser is an issue that urgently requires attention. Indeed, in a future where the scarcity of fossil fuels and the need to reduce GHG emissions will put pressure on energy supplies, this is a vital consideration. The cost of manufactured fertiliser is likely to climb as finite energy resources are needed for other purposes.[24]

As we have already seen in the case of oil and tar sands, as fossil fuels get scarcer and more expensive to produce, a shift into so called 'non-conventional' resources can take place, with devastating environmental consequences.[25] In the case of natural gas, it is the development of shale gas, obtained by a process called 'fracking', cracking rock to release gas by pumping in pressurised water, chemicals and sand, which is now causing concern. In the USA, fracking projects have been blamed for incidents where water has become so contaminated that local residents have been able to set light to water delivered from their taps. The first attempt at fracking in the UK, at a test site in Blackpool, began last year, but has since been suspended following two minor earthquakes in the area. The Labour Party is now calling for a moratorium on shale gas projects. Apart from safety concerns, the extraction of shale gas is also controversial because of concerns that the chemicals could contaminate aquifers used for drinking water and farming. Scientists at Cornell University reported that the methane that leaks during shale gas extraction, contributes to GHG emissions. [26]

Price volatility

Price volatility for manufactured fertilisers has become a reality for farmers in the UK. Over the last four years, the price of ammonium nitrate rose from about £160/tonne in spring 2007, to peak at about £380 a tonne in spring 2008, falling again to about £180 a tonne in July 2009. The price has risen again to about £300 tonne in May 2011. The price of fertilisers is determined by a range of factors, but the price of natural gas is a key factor.[27] The spike in

food commodity prices during 2008 had an impact as farmers increased fertiliser use to boost yields, increasing fertiliser demand. The price of oil affects the cost of transporting fertiliser.[28]

Greenhouse gas emissions

GHG emissions result from the production of ammonia, the production of nitric acid to make ammonia nitrate, and for converting this solution into a solid product. They also arise from transport and storage. It is estimated that fertiliser production is responsible for about 1.2% of the total emissions of GHGs in the world (consisting of 0.3% of pure CO_2, 0.3% as N_2O and 0.6% as flue gas CO_2).[29] One estimate of the GHG from the production of one kilogram of manufactured nitrogen put the figure at 5.465 kg of CO_2 equivalent,[30] although other calculations range from 3.294 to 6.588 kg.[31]

Using manufactured nitrogen

Historically, in many countries, manufactured fertilisers have been a relatively cheap source of nitrogen for agriculture. Fertiliser consumption in Europe has increased dramatically over the last century and as a continent it had the highest use per unit of agricultural in the world by the 1980s. However, in the early 1990s, following the reform of the Common Agricultural Policy and the collapse of the Eastern European economies, there was a significant fall in use.[32] Nevertheless, Europe has stored up a nitrogen inheritance of unexpected environmental effects'.[33]

Today, it is China that is the largest producer and consumer of manufactured fertilisers, at 40% of global consumption.[34] India accounts for 20% of consumption, whilst Africa only 2%. Europe still has a relatively large share of world use at 13%.[35]

Application rates are highest in China at about 250kg/ha per year, compared to rates in other parts of the world of between 50 and 100 kg/ha per year.[36]

When more nitrogen is put on farmland than is taken up by the growing crop, a nitrogen surplus is created. This can occur because too much nitrogen is being added, or it is added at the wrong time, or in the wrong form, for it to be taken up by growing crops. This can lead to environmental problems as surplus nitrogen may be lost to ground and surface waters as nitrate, or to the atmosphere. The environmental loss is significant with estimates that 40-70% of the fertiliser nitrogen applied to crops being lost. In animal farming there are larger losses with 50-90% lost to the environment when measured in terms of live-weight.[37] Of course, surplus nitrogen is also a financial loss to farmers if they are using nitrogen fertilisers that are not contributing to the growth of crops.

At a lower intensity, these negative effects can also occur with the use of biologically-fixed nitrogen, if used inappropriately, although on a global scale it is the use of manufactured nitrogen fertilisers that is causing the main concern today. Risks of nitrogen pollution also arise from the spreading of farmyard manures and slurry on farmland, urine and dung deposition by animals, and the use of compost. These are not sources of 'new' fixed nitrogen from the atmosphere, but the effect of their use is to concentrate nitrogen in particular places, where it can be beneficial for crop growth. However, where there is too much, or it is not managed properly, it can cause environmental problems.

Environmental pollution and impacts on human health

Surplus nitrogen can be lost through the leaching of nitrate or through gaseous emissions to the

The problems with manufactured nitrogen

atmosphere in the form of ammonia, nitrogen oxides or nitrous oxide. The fact that an emitted molecule of nitrogen can be transformed to different pollutants along its transport pathway in the environment leading to a cascade of effects, is a particular worry.[38]

Nitrate leaching

Nitrate leaching is a problem because nitrate is soluble and an anion (negatively charged) so it does not bind to soil surfaces which are also dominantly negatively charged making it susceptible to loss in drainage. Nitrate leaching can lead to eutrophication and acidification in fresh waters, estuaries and coastal zones which can lead to biodiversity loss, toxic algal blooms and dead zones, as well as reef degradation that can harm shellfish and fisheries. Indirect emissions resulting from nitrate leaching into aquatic systems are considered a potentially important source of N_2O emissions to the atmosphere, although its magnitude is still under debate.[39]

Volatisation of ammonia

Another major pathway of nitrogen loss from agricultural systems is the volatisation of ammonia (NH_3) from soils and its subsequent deposition elsewhere, which can have a range of ecological impacts in the downwind ecosystems. These include increased rates of soil acidification, changes in plant community composition favouring nitrogen loving species, greater nitrogen fertility resulting in increased fluxes of nitrogen oxide (NOx) trace gases, and greater sensitivity by the vegetation to drought or frost.[40] Ammonia is easily oxidised to nitrate and can become at risk of leaching as described above.

Nitrogen oxides

Increased emissions of nitrogen oxides (NOx) gases from burning fossil fuels and biomass and fertiliser use, all contribute to high atmospheric levels. High NOx levels lead to the production of tropospheric (low level) ozone (O_3). For humans, O_3 exposure can lead to a range of respiratory problems. On land, high levels of tropospheric ozone can cause crop damage.[41]

Of particular significance is nitrous oxide (N_2O), known to be a powerful greenhouse gas with a global warming potential (GWP) of 298 times that of carbon dioxide. It is now also considered the major anthropogenic emission causing stratospheric ozone depletion.[42] N_2O makes up 54% of the UK agricultural sector's GHG emissions.[43]

Impact on soil organic matter

Soil organic matter (SOM) is made up of living organisms, active partially decomposed plant and animal residues, and more stable organic matter often called humus.[44] SOM plays a key role in improving soil structure, increasing water availability, the sequestration or carbon, and as a storehouse of plant nutrients including organic nitrogen.[45] Nitrogen represents about 5% of the dry weight of soil organic matter (SOM).[46] Using a farming system that maintains and builds soil organic matter, and that contains a store of organic nitrogen that can be potentially mineralised for plant use, is critical because increasing the proportion of nitrogen for crops that can be met by nitrogen from the soil is key to reducing dependency on external nitrogen inputs.[47]

It is argued by some that biologically-fixed and manufactured nitrogen are indistinguishable once in organic form and equally become potential sources for N_2O emissions (and other nitrogen losses).[48] However, there is now evidence that farming systems using these different types of nitrogen do function differently and that legume-based systems are better at not only building soil

organic matter generally,[49] but specifically lead to an increase in soil organic nitrogen that is available to crops through mineralisation.[50]

A letter to the journal *Nature* (1998) found that contrary to conventional wisdom, the level of nitrogen in soils is not just controlled by the net input of nitrogen, but that the *type* of nitrogen was also important. On research plots, whilst the legume-based cropping system and a conventional 'fertiliser-driven' system had similar levels of nitrogen inputs, the legume-based system had higher retention of nitrogen in the soil in the long term, and less nitrate leaching, than the system using manufactured fertilisers.[51] The authors point to studies that have shown that there are differences in the partitioning of nitrogen from organic versus mineral sources, with more legume-derived nitrogen than fertiliser-derived nitrogen immobilised by soil micro-organisms in SOM.[52] They suggest that if immobilisation is lower in the manufactured fertiliser system compared with the legume-systems, it could explain the greater rates of leaching of nitrate in the fertiliser system. They suggest that the use of low C:N residues for soil fertility combined with a range of plant species within the farming system that can scavenge soil nitrogen during periods in which summer crops are not active, can improve nitrogen balances.[53]

This is a strikingly under-researched area given that the first evidence of a problem was published in 1927. Research from the Jordan Plots in Pennsylvania, USA, showed that manufactured nitrogen fertilisers have a deleterious impact on soil organic matter.[54] This finding was confirmed in a 1938 article concerning long-term soil changes at Sanborn Field in Missouri, USA.[55] Indeed this work supports the concern that the organic movement has had for decades about the long-term sustainability of a farming system reliant on manufactured nitrogen fertilisers. The loss of soil organic matter was a problem diagnosed by one of the founding members of the Soil Association, Sir Albert Howard, in 1947:

'The use of artificial manure particularly sulphate of ammonia: even where there is a large safety margin, i.e. a large reserve of humus, such dressings do untold harm. The presence of additional combined nitrogen in an easily assimilable form stimulates the growth of fungi and other organisms which, in the search for organic matter needed for energy and for building up microbial tissue, use up first the reserve of soil hummus and then the more resistant organic matter which cements soil particles.'[56]

Of perhaps most significance, is new scientific research from the University of Illinois that also challenges conventional wisdom, and points to the use of manufactured nitrogen causing the loss of soil organic matter by stimulating the activity of soil micro-organisms so that under some circumstances they breakdown organic matter at a greater rate than new organic matter is being added to soils through plant residues.[57] This is likely to be because the manufactured fertiliser provides the micro-organisms with easy-to-use nitrogen, lowering the carbon to nitrogen ratio of the organic matter, and increasing its decomposition rate. The potential impacts of this are very serious and include the reduced ability of soils to store carbon, and thus reduced ability to mitigate climate change, as well as to store organic nitrogen, leading to higher nitrogen losses to the environment.

As a result, the scientists doing this research concluded that 'the scientific basis for input-intensive cereal production is seriously flawed. The long-term reliance on continued practices will be a decline in

The problems with manufactured nitrogen

soil productivity that increases the need for synthetic nitrogen fertilisation, threatens food security, and exacerbates environmental degradation'.[58]

This research has not been without controversy,[59] but research is urgently needed to see if such results are replicated in further studies.

The Government should investigate the likelihood that legume-based organic systems and those using manufactured nitrogen behave differently, especially in terms of retaining soil organic matter. There is an urgent need to understand the consequence of this for long-term soil fertility, reducing GHG emissions, storing carbon in soil and reducing our dependence on manufactured fertilisers.

What action is being taken?

A variety of technological developments, as well as policy initiatives and changes in farming practices are being suggested as ways of tackling the nitrate pollution, energy use and GHG emissions arising from manufactured nitrogen use.

Legislative developments

European legislation is now in place to try and tackle nitrate pollution. Under the EC Nitrates Directive (91/676/EEC), land that drains into fresh or ground waters polluted by nitrates has to be designated as a Nitrate Vulnerable Zone (NVZ) and farmers with land in NVZs have to follow mandatory rules that limit application of nitrogen and modify timings.[60] Non-compliance with the rules risk a deduction from the EU funds transferred to the UK to pay the Single Farm Payment. The EC Nitrates Directive also requires Member States to introduce a voluntary Code of Good Agricultural Practice for farmers to control nitrate loss and to protect against nitrate pollution. Defra now also provides advice to farmers in the form of a Fertiliser Manual and Good Nutrient Management Guidance. About 50% of farms in the UK have a Nutrient Management Plan.[61]

The European Nitrate Assessment reports that there are a number of countries with decreasing average nitrate concentrations in shallow ground waters following the implementation of the EU Nitrates Directive, although the decreases are modest and a significant number of monitoring stations show increasing concentrations. Reductions in nitrate concentrations follow from reductions in the surpluses of nitrate in the soil surface balance, and in Europe these have on average decreased since 1990, due to several factors including the Nitrates Directive but also structural changes in agriculture following changes in the Common Agricultural Policy designed to curb overproduction and enhance environmental protection.[62]

Fertilisers that produces less GHG in manufacture

Reducing the amount of GHG produced in the manufacture of fertilisers is possible through improving the energy efficiency of ammonia production and reducing the N_2O emissions produced during the production of nitric acid for ammonia nitrate.

The EU consider that 'Best Available Technology' (BAT – usually the most advanced technology, and the reference point for building new plants), should be able reduce emissions to 3.6 kg CO_2 equivalent per kg of nitrogen for ammonia nitrate fertilisers.[63] It is likely that competitiveness and energy-efficiency imperatives will mean that new gas-based ammonia plants will use this technology. However, the International Fertiliser Industry Association, (IFA) representatives of the global fertilser industry, admit that it will take decades to get this technology up and running.[64]

For existing plants, Best Practice Technologies (BPTs - implies that the technology is currently economically viable) can be used to improve performance. The IFA claims that up to 25% of the sectors' current GHG emissions could be avoided through the adoption of BPTs, with two-thirds of this saving achieved through N_2O abatement in nitric acid production for ammonium nitrate.[65] The fertiliser manufacture Yara claims to have developed and implemented a catalyst technology for reducing N_2O emissions from nitric acid plants by up to 90%. This brings the GHG emissions down to 'below 4 kg CO_2 equivalent per kg of nitrogen'[66] (compared to an average of 5.5kg).[67] The industry admits while some technologies could achieve important reductions in the medium term, it will be decades before costly technology revamps are widely integrated into older plants as part of capacity upgrades.[68] Even with these reductions, fertiliser manufacture will still

What action is being taken?

involve the use of fossil fuels as a feedstock and a source of energy, and huge emissions of greenhouse gases.

Manufacture using renewable sources

Theoretically, it is of course possible to make manufactured fertilisers using energy and hydrogen derived from non-fossil fuels, such as nuclear, wind and solar, and such developments are anticipated in the future. There is some evidence of test plants being built, such as a wind-powered plant at the University of Minnesota.[69] However, currently, there are no public signs that the fertiliser industry is considering renewable sources in its policy on tackling GHG emissions, and available worldwide statistics show no sign of the development of any fertiliser plants making use of non-fossil fuel for ammonia production.[70]

Furthermore, on a global scale the current trend seems to be in the opposite direction, with the use of coal increasing by nearly 10% since 2000, in China.[71] The IFA predicts that coal-based ammonia synthesis is expected to increase in coming years. This is a worrying development given that the energy requirement to produce a tonne of ammonia is significantly higher in coal-based plants than gas-based, and coal plants produce 2.4 times more CO_2 per tonne of ammonia than natural gas plants.[72]

Authors of a study into the future of nitrogen supplies commissioned by the Government Office of Science, find it 'difficult to envisage a competitive system on non-fossil fuel', compared to a natural gas based system. They argue for natural gas to be ring-fenced as supplies become scarce, and the energy deficit created made up by other means. Such a suggestion fails to address any of the problems created by the use of the fossil fuels in the first place, and puts further pressure on renewable energy supplies.[73]

GM Nitrogen-fixing crops

It has been suggested that non-legume crops such as wheat could be genetically-engineered to fix their own nitrogen. However, a crop's ability to fix nitrogen is not determined by just one gene but appears to rely on a complex relationship between soil bacterium and the crop, making genetic modification difficult or impossible.[74] One approach proposes the introduction of the enzyme nitrogenase into cereal crops, but the tension between the energetic need for oxygen and the denaturing effect of oxygen on the enzyme is unresolved. It has also been proposed that there is the theoretical potential for the establishment of root nodules colonised by nitrogen-fixing bacteria on cereals. However, a likely obstacle is the energy requirement, which would probably reduce the yield of the crop significantly.[75]

It is unlikely that any such developments, even if they were found to be technically feasible, would be available in the foreseeable future.[76] The Government commissioned Foresight report into the future of food and farming admits that the introduction of nitrogen fixation into non-legume crops is unlikely to contribute significantly to raising agricultural productivity until at least the latter end of the 40-year period considered by the report.[77]

Nitrification and urease inhibitors

Nitrification inhibitors slow the conversion of ammonium to nitrate by microbial processes, and thus have the potential to reduce emissions of N_2O. Urease inhibitors slow the conversion of urea and urine to ammonium and thus to nitrate. They are widely used in New Zealand. They have not been widely used in the UK, but are now being considered

as a way to reduce N_2O emissions from animal urine and dung, but also from manufactured fertilisers.[78] Research to look at their effectiveness in the UK has been funded by Department of the Environment, Food and Rural Affairs (Defra).[79] Their effectiveness assumes that the inhibitor makes good contact with the fertiliser or urine patch, and that it is applied at the right time and to the right fertiliser type. However, they are expensive and significant reductions in manufactured nitrogen use would be needed to make them cost-effective.[80] The fertiliser manufacturer Koch has launched a urea fertiliser treated with urease inhibitor to reduce ammonium volatilisation.[81]

Increase efficiency of use

The most commonly recommended solution to reducing the climate change and pollution impact of manufactured fertilisers focuses on increasing nitrogen use efficiency in crop and animal production.[82] The Agricultural Industry Greenhouse Gas Action Plan is a voluntary scheme that aims to reduce emissions by 3Mt CO_2 equivalent by 2020 through measures that include more efficient crop and grassland production by optimising the timing and frequency of fertiliser applications.[83] Precision farming technologies based on GPS and soil mapping can improve the efficiency of farm operations, and can make fertiliser application more efficient. The fertiliser industry has produced management tools for farmers to optimise their fertiliser use. For example, Yara claims that its 'N-Sensor' tool increases efficiency and reduces the carbon foot print of fertiliser by 10-30%.[84] Research by scientists in Germany found that site-specific fertilisation had the potential to reduce N_2O emissions, but that variations in climate, especially rainfall patterns, had to be taken into account for such measures to be effective.[85]

Scientific advice to the Committee on Climate Change found that improved timing of mineral fertiliser nitrogen application and avoiding nitrogen excess are cost effective measures to reduce N_2O emissions from agriculture.[86] However, the Committee on Climate Change has said that more efficient use of nitrogen fertilisers, as well as other minor changes in management practices, will not be enough for the agricultural sector to meet its share of emissions reductions under the Climate Change Act, and that post-2030, more radical measures should be considered.[87]

The need for a different agricultural system

These suggestions for reducing nitrogen losses and the GHG impact of our dependence on manufactured fertilisers clearly have either economic limitations or technological impracticalities, will have only a limited impact on the problem, or still leave agriculture reliant on scarce fossil fuels, in which case, the price of food is likely to continue to increase as fossil fuels get scarcer and more expensive. Instead, as the UK Government's Climate Change Committee has said, more radical changes are needed. The solution lies in changing how we farm towards agricultural systems that do not need manufactured nitrogen fertilisers at all, but use nitrogen-fixing crops, such as legumes. Such systems must implement farm management practices that minimise both the need for newly-fixed nitrogen inputs, and losses to the environment, especially N_2O.

As an agricultural system that does not allow the use of manufactured nitrogen, but makes use of legumes to fix nitrogen, we review the current evidence on the extent to which organic systems can meet this double challenge of reducing nitrogen pollution, especially N_2O emissions, and building stores of soil organic nitrogen.

Organic systems: building fertility without manufactured nitrogen

In organic farming systems, the use of manufactured nitrogen is not allowed, and new inputs of nitrogen come from the fixation of atmospheric nitrogen by legumes. The use of legume based leys as part of a crop rotation has been declared 'the cornerstone of the organic philosophy'.[88] Soil Association standards advise that there should be a balance of cropping and clover leys in the rotation, and they should include a mixture of nitrogen-demanding and nitrogen-fixing crops. A supplementary boost of nitrogen is often given during the fertility depleting phase, by the growing of other leguminous crops such as field beans or peas. The addition of manures and composts and the recycling of crop residues also returns nitrogen to the soil, but there are restrictions on how much can be added to a given area in a year.[89]

Using clover in grassland to fix new nitrogen, rather than manufactured nitrogen, is a practice that can be readily adopted by non-organic farmers. It has multiple benefits in addition to avoiding the economic and environmental costs associated with use of manufactured nitrogen. A grass and clover sward can deal better with drought and wet conditions due to a better rooting system, and a better quality sward or silage will reduce dependence on purchased feeds. The aim is to produce a sward which has plenty of clover to produce the optimum amount of nitrogen per hectare, and the same yield as grass only leys without the nitrogen fertiliser.[90] The use of winter cover crops is another practical modification. Research gathered from a range of sites in Northern Europe, found significant economic benefits of organic legume-based production systems relative to conventional grass-based systems of production.[91]

The amount of nitrogen fixed by different legumes depends on a number of factors: there is an inherent capacity of the crop to fix nitrogen, but this is modified by the crop's growing conditions, crop management and the length of time for which the crop is grown. Legumes prefer to get their nitrogen from the soil, so if a soil has high levels of mineral nitrogen already, the amount of nitrogen fixed is likely to be less.[92] Estimates have the amount fixed by white clover-grass leys at 150-200 kg nitrogen/hectare/year, red clover leys up to 240 kg, lucerne up to 500 kg and field beans up to 200 kg. It should

be remembered that harvesting forage or grain will remove much of the fixed nitrogen, as will removing straw and crop residues from the field, and therefore it will not be available to the crops, although of course they can be re-used on farm.[93]

For the newly-fixed organic nitrogen from legumes to be used by the next crop, soil organisms have to transform it to plant available forms, in a process called *mineralisation.* This commonly occurs through the ploughing in of the legume crop or ley in order to prepare a weed free seed bed for the next crop, although alternative methods that reduce cultivation are now being trialled (see below). The rate of mineralisation is heavily dependent on environmental conditions, such as soil moisture and temperature, soil texture, as well as the composition of the crop material. Whilst this is essential for the crops to be able to use the nitrogen, the mineral nitrogen is then susceptible to loss.[94] As with non-organic agriculture, this nutrient must be properly managed to avoid unnecessary losses.

The Government should provide financial incentives to help farmers implement measures such as the replacement of manufactured fertilisers with clover in grassland and the use of winter cover crops. These should be included as part of the greening of Pillar 1 of the Common Agriculture Policy.

Reducing nitrogen losses from agriculture

There are several different ways that the impact of nitrogen from agricultural systems can be reduced and these are discussed here, with a specific look at what evidence there is for organic systems to reduce nitrogen losses.

Reducing nitrogen surpluses

With a relatively high reliance on internal nitrogen cycling, organic systems are usually found to have lower levels of nitrogen inputs than non-organic systems. However, when looking at overall losses, this needs to be considered in relation to the amount of nitrogen that is used by growing crops. At the simplest level if there is an excess of nitrogen in a farming system over that required by growing crops, it will lead to its accumulation in the soil and there is a risk that this will be lost to the environment, causing pollution. Thus the calculation of nutrient balances that measures the nitrogen inputs and nitrogen outputs of a farm can indicate if there is a nutrient surplus that might lead to a nutrient loss and subsequently pollution.[95]

A review of studies by Stolze *et al* (2000) found that nutrient balances on organic farms are lower than on non-organic ones and argued that, 'in organic farming, the risk of water and air contamination as a consequence of nutrient surpluses is low'.[96] Shepherd *et al* (2003) also found that nutrient surpluses are smaller for organic than conventional farms, when comparing the same farm types. They concluded that this has important implications for the environmental effects of organic farming as smaller nutrient surpluses will impact on the nitrogen losses from these systems.[97]

Improving nitrogen use efficiency

The most important reasons for this smaller surplus of nitrogen on organic farms is the general ban on manufactured fertilisers, and the limited livestock stocking density per land area. In economic terms, the opportunity cost (the cost to produce nitrogen on-farm) of nitrogen on organic farms can amount to from seven to sixteen times the cost of manufactured nitrogen fertiliser. Therefore, there is a special economic interest for organic farmers to avoid wasting nitrogen through a surplus.[98]

Making the most efficient use of limited nitrogen inputs will become a key driver for agricultural systems in the future. This should also provide an incentive for more efficient nitrogen use in organic systems. Research published in *Science* found that nutrient input (including nitrogen) in the organic systems to be 34-51% lower than in non-organic systems, whereas mean crop yield was only 20% lower over a period of 21 years.[99]

Improving nitrogen synchrony

A second critical point for reducing nitrogen losses is not just avoiding a surplus of nitrogen, but also ensuring that it is only available when growing crops are there to take it up. This stops a build up of mineral nitrogen in the soil. Synchronising supply and demand of nitrogen is very important. The nitrogen in manufactured mineral fertilisers and biologically-fixed nitrogen are made available to crops at different speeds. Mineral nitrogen in manufactured fertilisers can be immediately taken up by crops once applied, whilst organic nitrogen in legumes and other crop residues, and manure, has to be released by soil organisms into the soil before it can be taken up by crops.

In spring, crops have the largest demand for nitrogen for growth and leaf production (nitrogen is needed to produce leaf protein for chloroplasts). Matching nitrogen supply with demand from the crops is

important to maximise the efficiency of the farming system and minimise nitrogen losses. In principle, in non-organic farming, manufactured nitrogen fertilisers can be applied at the best time during the growing season, usually in several applications, in order to better match nitrogen supply and demand and increase efficiency.[100] However, in practice many factors may reduce the actual efficiency, and some farmers are more effective than others.[101] The danger with mineral nitrogen is that an application may result in higher levels of mineral nitrogen than can be taken up by the crop at any given time, and thus a build up of excess nitrate that can be lost to the environment.

In organic systems nitrogen mineralisation following the decomposition of organic matter is a slower process. It can be difficult reliably to manage and time nitrogen release in organic systems because environmental conditions, particularly temperature and moisture, effect microbial growth and activity, and in addition the type of organic matter being decomposed can affect the rate of release.

These biological processes are less able to release mineral nitrogen in the short intense bursts required for rapid plant growth.[102] However, it is possible, and advantageous, for organic farming systems to optimise nitrogen synchrony by a variety of management practices. It is possible to select crop varieties and mixtures that will be mineralised and release their nitrogen at the required time to be taken up by the following crops.[103]

One of the key determining factors is the carbon: nitrogen (C:N) ratio of the organic matter that is being mineralised by soil organisms The decomposing organism uses carbon in soil organic matter as an energy source to access the nitrogen and other nutrients for growth from the breakdown of the materials. If there is not enough nitrogen in the decaying organic matter for the micro-organisms they will take up nitrogen already present in the soil, depleting the soil pool – this process is called immobilisation.[104] If however there is nitrogen in excess of the soil organisms' requirement, mineral nitrogen will be released. So, young green materials with C:N of 15 or less will break down rapidly and release nitrogen, whilst older more 'woody' material with a C:N of 40 or more will break down more slowly and release nitrogen over a longer period. For example, wheat straw will decompose much more slowly than clover. Composted materials decompose slowly in the soil because they are relatively stable, having already undergone a significant amount of decomposition.

It is therefore possible to use different green manures alone or in combination to release nitrogen at different times, as the following crop grows. This has been considered ambitious.[105] However, the Legume LINK project is currently investigating how mixtures of legume and grass species can be tailored to optimise the amount of nitrogen that is fixed, transfer the nitrogen to the subsequent crop with the appropriate timing, as well as perform reliably under local environmental conditions.[106]

The timing of the ploughing of the legume ley and the establishment of new crops should also be considered. Autumn ploughing of leys is problematic from the perspective of nitrogen as mineralisation occurs when it is not the peak time for crop growth and nitrogen demand. (Nitrate leaching can be a problem; see next section). Winter wheat develops slowly during the autumn and significant levels of nitrate may be lost by leaching before the spring, when the main demand from cereals occurs.

Reducing nitrogen losses from agriculture

It is possible to ensure better synchronicity of supply and demand of nitrogen through the farming cycle by minimising the amount of time that fields are left exposed without any vegetation to take up any available nitrogen. Spring cultivations and planting could improve nitrogen use. Autumn cultivations followed by cover crops or green manures, as they are sometimes known, and then spring planting is another solution. These crops are usually nitrogen 'holders' or nitrogen 'lifters' such as mustard, turnips or phacelia that are not nitrogen-fixing and therefore do not provide any new nitrogen but do stop nitrogen being lost over the winter. They may also act as catch crops that can be used for grazing. Undersowing leys or cover-crops into a near-mature crop can also help reduce N losses.[107] This is as applicable to non-organic as well as to organic systems, where it is a requirement of Soil Association standards that the time that the soil is left uncovered is minimised, for example by using green manures.[108]

It may be possible to avoid the ploughing of legume leys altogether and minimum tillage systems where crops are direct-drilled into clover are currently being trialled.[109] It also seems that thoroughly mulching green manures before incorporating them into the soil will slow down the release of nitrogen because they are relatively stable, having already undergone a significant amount of decomposition.[110] There may also be advantages in developing perennially-based cropping systems as perennials are able to take up soil nitrogen when annual crops are not. For example, alley cropping plantings that involve sowing grain crops in the space between rows of legumes or actinorhizal trees or shrubs, and alfalfa/grain intercropping. There have been perennial wheat trials in the USA.[111] Nitrogen-fixing perennials can add substantial amounts of fixed nitrogen whilst the lateral network of roots from the perennial crops can recover excess water and leached nitrate that has escaped the crops or have been lost during the fallow period.[112]

Reducing leaching

Ammonium in the soil is rapidly converted to nitrate via the microbially-driven process of nitrification. Where there is water from precipitation or irrigation that exceeds crop demands, nitrate can then be washed from the soil as the water drains through it.[113] Most leaching takes place during the autumn/winter period, though nitrate can be lost at any time if there is sufficient rainfall to wet fully the soil. Nitrate leaching can occur if nitrate is added, or materials that are quickly converted to nitrate when drainage is occurring. Nitrate leaching can also occur if nitrate has built up in the soil in the autumn due to farming practices the previous season. This could be because a crop has been given too much nitrogen for its needs, or because there was no synchrony between the supply of nitrogen and the crop uptake. As previously noted, catch or cover crops, which scavenge nitrogen in the soil are effective at reducing nitrate leaching from what would otherwise be bare soil.[114]

The application of animal manures also poses a risk of nitrate leaching. The greatest risk is from late summer/early autumn applications of manures containing significant proportions of readily-available nitrogen. Studies have shown that losses are larger from slurries and poultry manures than from applications of farm yard manure (FYM) as its combination with straw gives it a lower nutrient availability.[115]

Various assessments of nitrate leaching on organic and non-organic farms, found that in general leaching was lower on organic farms, although where losses

are estimated on a per tonne of wheat rather than a per hectare basis differences are smaller. Ensuring best management on organic farms was also important to minimise leaching after cultivation of leys. The nitrate levels in organically managed soils tend to be lower than in non-organically because of the ban on manufactured nitrogen, lower stocking rates, and the production of farmyard manure rather than slurry. The nitrate load also tends to be lower because use of cover crops during winter, intercrops, under-sowing leys, and grass/clover leys of several years are all more common in organic than non-organic farming.[116]

There are two areas of potential problems by organic farming. The first is the composting of manure: if lots is stored and composted on non-paved surfaces, nitrate can leak into the water system. This can be avoided by certain practices such as covering the manure piles and including a pre-rotting phase on paved ground. The second is the management of nitrogen from legumes. Autumn ploughing can be problematic, as discussed above, and this is further discussed below in relation to N_2O.

Nevertheless, recognition of the benefits organic agricultural systems can bring to reducing nitrate pollution is reflected in the UK Government's decision to treat certified organic farmers as meeting the requirements of the EU Nitrates Directive.

Reducing N_2O emissions

N_2O is produced naturally by micro-organisms within the soil, and additions of nitrogen through farming practices tend to increase the amount of N_2O produced, so agricultural systems should aim to minimise emissions as much as possible, rather than to eliminate them. N_2O emissions arise from the use of manufactured fertilisers on soil; the application of animal manure, compost, and sewage sludge; urine and dung deposition on pasture by grazing animals; the nitrogen from crop residues including nitrogen-fixing, as well as from cultivation or land use change on mineral soils that causes nitrogen mineralisation.[117]

Two chemical reactions in the soil produce N_2O. Ammonium is rapidly transformed to nitrate by the process of *nitrification* whereby micro-organisms in the soil transform ammonium (NH_4+) to nitrate (NO_3-). N_2O is a by-product. A second process, *denitrification,* involves the transformation of nitrate (from the nitrification process or from the application of nitrate fertilisers) to N_2. N_2O is again a by-product. Under some conditions, N_2O can be converted to N_2 instead of NO_3-. Despite this connection, these two processes will not occur at the same place in the soil at the same time because the nitrification process requires an environment rich in oxygen (aerobic), whilst the denitrification process requires the opposite (anaerobic).[118]

As these processes producing N_2O both require nitrogen, the actions outlined above, ensuring lower levels of nitrogen inputs and better synchrony, will help reduce N_2O emissions. N_2O emissions can also be indirectly produced from nitrate that has been leached into water systems, and when nitrogen from ammonia volatilisation and NOx are later deposited.[119] However, there are other specific management practices that can be useful in reducing N_2O emissions.

The oxygen availability in the soil is a major influence on the rate of N_2O production as nitrification is an aerobic process. The optimum soil water content for nitrification is in the range of 30-60% water-filled space, whilst the optimum pH is thought to be pH 5.5-6.5.[120] For denitrification there needs to be an adequate supply of nitrate and anaerobic conditions.

In general, increases in N_2O will occur with increases in the concentration of ammonia and nitrate in the soil and with increasing soil wetness and soil density. However, N_2O emissions may decrease when the soil becomes too wet, as N_2O is further reduced to N_2. Soil conditions play an important role in determining the influence of soil cultivation irrigation and drainage on N_2O emissions. The resulting interactions are complex and difficult to predict or manage. If ploughing and drainage occur on a heavy soil, where denitrification to N_2 dominates over N_2O, then the rate of N_2O production would increase. However, on a less heavy soil, the opposite might be the case. In the case of irrigation, this might provide the anaerobic conditions required for denitrification. This may increase N_2O emissions, although on a heavier soil, this might promote denitrification to N_2, thereby reducing N_2O emissions.[121]

Comparing the emissions from organic and non-organic farming systems

Scientific evidence shows that the lower nitrogen inputs in organic farming systems can lead to lower N_2O emissions compared to non-organic farms on an area basis, although research comparing the N_2O emissions from the two farming systems is limited. Some of the research is based on actually measuring N_2O emissions on the farm, whilst other studies have estimated emissions using models.

Of the five peer-reviewed studies using field measurements to compare the N_2O emissions from organic and non-organic systems, two found higher emissions on the non-organic systems (Petersen *et al*, 2006[122] and Flessa *et al*, 2002[123]) and two found no significant difference, but significantly these two did not take into account the emissions from the production of the manufactured fertiliser in the non-organic systems (Chirinda *et al,* 2010[124] and Kramer *et al*, 2006[125]). The fifth found lower N_2O emissions on the organic farm compared with a non-organic farm without livestock, but higher than the non-organic with livestock, but again did not include emissions from artificial fertiliser production (Syvasalo *et al,* 2005[126]).

Of the other three field measurement studies (not peer-reviewed) two found lower emissions in organic systems (Lynch, 2008[127] and Hansen, 2008[128]) whilst the third did not (Dorsch, 1999[129]). Of the peer-reviewed studies modeling the comparative N_2O emissions, all three found lower levels of N_2O in organic farms compared to non-organic (Kuestermann, 2008,[130] Stalenga and Kawalec, 2008[131] and Nemecek *et al*, 2011[132]).

When comparing the N_2O emissions from organic and non-organic farming, it is important to consider the whole farming system because emissions may vary significantly between different parts of the rotation. Whilst these studies compared N_2O emissions on an area basis, some of them also considered the emissions on a product basis, with mixed results. For example, Flessa *et al* (2002) found no difference, whilst Nemecek *et al* (2005) found emissions lower for organic, and Syvasalo *et al* (2005) found emissions slightly increased for organic on a yield basis, but again this study did not include emissions from the production of manufactured nitrogen. However, Flessa *et al* (2002) note how assigning N_2O emissions to a specific crop is problematic because emissions can be considerably influenced by the crop rotation, in particular by the type of crop and the management during the previous year.

Why may organic farming systems have lower N_2O emissions?

Lower nitrogen inputs

Conventional wisdom is that the level of N_2O emissions from a particular farm are controlled by the amount of nitrogen going into the farm. In fact, the estimates for UK Inventory GHG emissions are calculated using the Intergovernmental Panel on Climate Change (IPCC) standard methodology for Tier 1 calculations, which uses a default emission factor to calculate N_2O emissions of 1% of the nitrogen source.[133] With this assumption organic systems, with lower levels of inputs, have comparatively less N_2O in modeling studies. Measurements taken in fields studies by Flessa *et al* (2002) and Petersen *et al* (2005) also found that nitrogen input was a significant determinant for N_2O emissions from agricultural soils, and thus were lower in organic than non-organic systems.

Nevertheless, it is clear that given the complexity of biological processes in the soil, as previously discussed, that many factors control how much mineral nitrogen is available to be lost, potentially as N_2O. The IPCC acknowledge that environmental factors, management-related factors, including the differences between legumes and non-leguminous arable crops, will have an impact on N_2O emissions and that countries can 'disaggregate' their data on

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this basis (Tier 2).[134] All the previously discussed practices that result in smaller nitrogen surpluses, better synchronicity and less risk of leaching will help to reduce N_2O emissions. There are several other factors that may lead to lower N_2O emissions in organic systems:

Lower cattle density

On grazed grassland N_2O emissions can be significant from dung and urine patches, and from areas in the soil which have been compacted by the treading of grazed animals (causing anaerobic sites). As livestock densities tend to be lower on organic farms than non-organic, because stocking densities are controlled by organic standards, generally the potential for losses of N_2O is also likely to be lower.[135]

More soil organic carbon

The relationship between soil organic carbon (SOC) and N_2O production is not straightforward. SOC can increase rates of denitrification as it provides a carbon and energy source for denitrifiers, and also, as described already in the case of manure, can lead to the production of anaerobic zones where denitrification can take place. However, conversely, SOC can also affect the proportion of N_2O versus N_2 that is produced during the reaction: with more SOC, more N_2 than N_2O will be produced.[136] This is what Kramer *et al* (2006) found when they compared apple orchards under different management systems. Rates of N_2O emissions were not significantly different between the plots, but N_2 emissions were highest in the organic plots. In the organic orchard, with more soil organic carbon, the rates of denitrifier activity were higher, but these worked more efficiently, converting more of the N_2O to N_2. This had the advantage of reducing nitrate leaching.

More research is needed to understand the interaction between soil organic carbon and emissions of N_2O and what this means for organic farming systems that generally have higher levels of SOC than non-organic systems.[137]

Tillage

There is on-going debate about the impact of minimum (min) or no-till farming systems on GHG emissions, with no-till contributing to soil carbon sequestration, although the scale and permanence of such methods is debated. On organic soils significant N_2O emissions are produced from ploughing and other cultivations. However on mineral soils, research on min and no-till systems now shows that the positive impact of a significant proportion of the additional soil carbon may be off-set by increased N_2O emissions, resulting from no-till practices that lead to poorer aeration and increased denitrification rates. This effect is greatest in soils that are already poorly aerated.[138]

The effects of different tillage practices on N_2O emissions, and therefore the overall climate change impacts, needs more research.

It is important to remember that N_2O emissions are clearly affected by the environmental conditions that affect the actions of the microbial consortia that carry out the N_2O production including temperature, pH, organic carbon, soil water level and oxygen levels. Seasonal rainfall has been found to be very significant.[139] In particular, freeze-thaw events can have important effects on N_2O budgets.[140] There is uncertainty and great variation about how changes in these conditions affect N_2O emission[141] but they have the potential to partly foil the positive effect of lower nitrogen levels in topsoil.[142]

What are the potential N_2O hotspots on organic farms?

Despite evidence to suggest that the lower nitrogen imports into organic systems lead to lower N_2O emissions than in non-organic systems, there are two potential N_2O hotspots in organic systems:

Decomposition of manure

Research has found higher emissions after manure applications compared to mineral fertiliser application,[143] although this seems to vary with soil type with the differences much smaller on clay soils than sandy soils.[144] The higher emissions are thought to be because the decomposition of the manure involves high oxygen consumption, producing oxygen-deficient (anaerobic) environment that increases rates of denitrification, and thus higher N_2O production.[145] It has also been suggested that this may be to do with the additional carbon substrates that enhance soil respiration and result in greater denitrification.[146] Other studies have found that significant N_2O emissions from organic fertilisers are more likely to come from the process of nitrification.[147]

Incorporation of legumes

The main nitrogen source for organic farms is typically the incorporation of legumes (as part of grass leys or green manures) in preparation for the sowing of crops, and this is also often seen as the highest risk for N_2O emissions from organic systems.[148] As previously discussed, when these are ploughed in and micro-organisms mineralise the nitrogen, it is made available to the following crops. If they do not take it up, it can lead to nitrate pollution and increased N_2O emissions. The rate of mineralisation depends in part on the type of legume. Clover has a low C:N ratio of 13 and therefore will break down rapidly. This 'flush' of nitrogen needs to be managed properly, to be fully utilised by the farming system, and to avoid N_2O emissions, and other nitrogen pollution. Key practices for farmers in managing nitrogen have already been discussed and are outlined in the executive summary.

In addition to the UK Legume LINK research project, there is an urgent need for further research into best practice for organic farmers on how GHG emissions from organic systems can be minimised through the timing of agricultural practices such as ploughing of leys, application of animal wastes, and crop planting. This should include innovative methods already being trialled on organic farms such as alternatives to ploughing clover leys, such as direct drilling into clover, and the use of perennially-based cropping systems, or alley-cropping legumes and grain crops.

In the UK, our GHG Inventory is currently based on Tier 1 emissions factors – a standard 1% calculation. However, the Government is funding the 'InveN_2Ory' project to move these calculations to Tier 2 for N_2O through measured and modelled emissions factors for N_2O emission from a range of soils, farming systems and climatic zones of the UK. The project is not however looking at organic systems, or even clover-leys. This seems a significant omission given that the project aims to 'future proof the inventory to take account of potential mitigation methods'.[149] Given the pressures described in this report, it will be imperative that legume-based systems such as organic play a significant role in our future farming systems.

The Government should fund research that looks in detail at N_2O emissions from organic systems

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to bring scientific understanding to the same level as will be provided by the 'InveN_2Ory' project for non-organic farming practices.[150] This will contribute to the 'future-proofing' of UK GHG Inventory, and will ensure that emissions from organic systems are represented using an accurate emissions factor.

A new way forward: changing agriculture, changing diets

Alongside the concern over nitrogen, there is growing political awareness that small modifications to our current food and farming system will not be sufficient to deal with the other problems we are facing, such as climate change, resource-use and diet-related ill health. More radical changes in both how we farm and what we eat will be needed in order to reduce, and eliminate, our dependency on manufactured nitrogen. Changing or 're-balancing' diets is now being tentatively considered by policy-makers and scientists as a way to reduce the climate change and other environmental impacts of agri-culture.[151] The Government-commissioned Foresight report in the future of food and farming[152] concluded that 'demand for the most resource-intensive types of food must be contained'.

With 50-90% of nitrogen used in livestock farming lost to the environment, the scientists who compiled the European Nitrogen Assessment called for a lowering of the human consumption of animal protein as a way of also tackling nitrogen excesses.[153]

Research into the impact of nitrogen use and pollution as a consequence of a shift in diets in the UK to lower consumption of meat and dairy products, especially from animals fed on grain rather than grass, should be commissioned to accompany existing evidence of the climate change and health benefits.

A shift to organic farming systems will necessarily mean a change in diets in the countries of the Global North, like the UK, to a diet with less meat overall, with the focus of reductions being intensively produced white meat and grain fed beef, with proportionately more grass-reared beef, lamb and mutton. Alongside more seasonal fruit and vegetables, starchy carbohydrates and whole grains, and less processed foods, and less unsustainable fish and meat and dairy, this will provide a healthier diet.

The multiple problems with our dependency on manufactured nitrogen provide further reasons why, in addition to the environmental impacts, the expansion of unhealthy diets and the reality of peak phosphorus, calls to vastly increase food production by 2050 through the further intensification of agricultural systems using genetically-modified crops and manufactured fertilisers is not just undesirable, but actually impossible. As the recent IAASTD report, written by over 400 scientists and supported by over 60 countries, recommended, ensuring food security requires a new food and farming system that is based on the principles of agro-ecology.

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written by Isobel Tomlinson

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