FIXING NITROGEN

The challenge for climate, nature and health

Contents

Foreword 4

Executive Summary 5

Too much of a good thing 8

Nitrogen fertiliser – the overlooked driver
of climate change 9

Excess nitrogen as a risk to nature 13

Case Study 1: Livestock ammonia pollution
damaging ancient woodlands 17

Case Study 2: Putting wildflower meadows back
into the farmed environment 19

The impact of nitrogen on public health 21

Nitrogen: The big questions 23

The way through the nitrogen challenge 26

References 28

Foreword

As a farmer, nitrogen management is key to everything I do. It is the primary determinant of crop yield, being the most important of the macronutrients that drive plant growth.

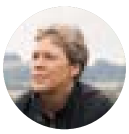
The invention of synthetic nitrogen has been arguably one of the most significant innovations in the history of agriculture – releasing farmers from the constraints of rotational farming, allowing them to grow cereals and oilseeds year after year, without having to build nitrogen in the soil through restorative, nitrogen fixing plants like clover, peas and beans.

> My father called synthetic nitrogen 'sugar', and it's a good analogy. Just as sugar gives energy, but no nutrition, likewise with 'bag' nitrogen.

Repeated doses sap vitality and create dependence. Plant immunity to disease is compromised. Even more importantly, as this report outlines, the artificial fixation of nitrogen has led to much more of it in our environment than would be possible through natural fixation by leguminous plants. In the same way that we have released huge quantities of carbon dioxide through burning fossil fuels, so we have released huge amounts of reactive nitrogen, with both direct and indirect consequences.

Of course, it's not a simple case of synthetic nitrogen bad, naturally fixed nitrogen good. Nitrogen, and other nutrients like phosphorous, can leach from manures and ploughed grass leys, causing diffuse pollution of waterways and the atmosphere. All farmers need to manage nitrogen better. As an organic farmer, however, I have an especially strong commercial driver to do so. Retaining the nitrogen fixed during the fertility building part of my rotation is crucial to the success of my cash crops such as wheat and barley. I have every incentive to husband it wisely, apply enough manure but not too much, and grow cover crops over winter to prevent nitrogen, which is very water soluble and labile, from leaching away. Even so, we still have much to learn about how to do this to best effect, and often need to invest further, especially in manure storage and application systems, to minimise nitrogen losses.

Given that the amount of reactive nitrogen in our environment has already breached the safe operating space, this is an issue that deserves far more attention than is currently the case. We welcome the support of the Woodland Trust and Plantlife in doing so. I hope that you will find this report a useful contribution to the debate.



Helen Browning,
CEO of the Soil Association,
August 2020

Executive summary

Nitrogen is essential for life on earth and vital for food and farming. In excess, however, nitrogen becomes a damaging pollutant threatening climate, nature and human health. This report explores the challenges that the disrupted nitrogen cycle poses to our future, tackles some big unanswered questions and proposes a pathway forward.

Farming relies on reactive nitrogen to help crops grow. This was historically supplied through animal manures and the natural fixation of nitrogen by plants such as peas and beans. However, in recent decades, industrial manufacturing of nitrogen fertiliser has scaled up in the face of pressure to increase yields to feed a growing population. These synthetic fertilisers have initiated a massive increase of reactive nitrogen on earth with significant unintended consequences.

Climate: Scientists and policymakers have begun to realise that synthetic nitrogen fertilisers are a major contributor to climate change in two key ways: through the greenhouse gas emissions during their energy-intensive manufacture, and in the form of nitrous oxide emissions from the use of fertilisers in agriculture. Nitrous oxide is a potent and long-lived greenhouse gas, emissions of which need to fall near to zero to achieve the widely shared ambition of net zero greenhouse gas emissions. This is far from a reality and requires radical action to curb fertiliser manufacture and use.

Nature: Excess nitrogen has multiple impacts on the natural world. A recent global biodiversity assessment highlighted the build-up of reactive nitrogen in the environment as one of the most significant threats to global biodiversity. Two examples of those impacts feature in this report. One is of nitrogen in the form of ammonia escaping from intensive chicken units and deposited in ancient woodlands, damaging delicate plants and unbalancing the ecosystem. The other is fertiliser use, which has largely caused the loss of floral diversity of traditionally farmed landscapes. Nitrogen impacts are also felt in our rivers and seas, creating 'dead zones' such as in the Gulf of Mexico, where the excess nitrogen from intensive agriculture has left aquatic ecosystems devoid of oxygen and life.

Health: The health consequences of the wrong sort of nitrogen in the wrong place are widespread and serious. They include thousands of deaths annually in the UK, resulting when agricultural ammonia emissions combine with pollution from car exhausts in urban areas to create dangerous particulates in the air. And the health impacts of nitrogen impose more than a human cost: reducing the level of nitrates in drinking water to meet legal limits costs millions of pounds annually.

Evidence suggests that much existing reactive nitrogen in the form of synthetic fertilisers is not efficiently utilised and could be cut without compromising yields. More efficient use of animal manures and greater use of nitrogen fixing crops in rotations will be crucial to replace synthetic nitrogen as part of the process of rebuilding soil fertility.

The issue of global food sufficiency is complex and requires careful modelling and planning. It raises crucial questions of diet, and whether we can justify the current large-scale reliance on nitrogen inputs that underpin intensive livestock

© Emile Loreaux / Greenpeace

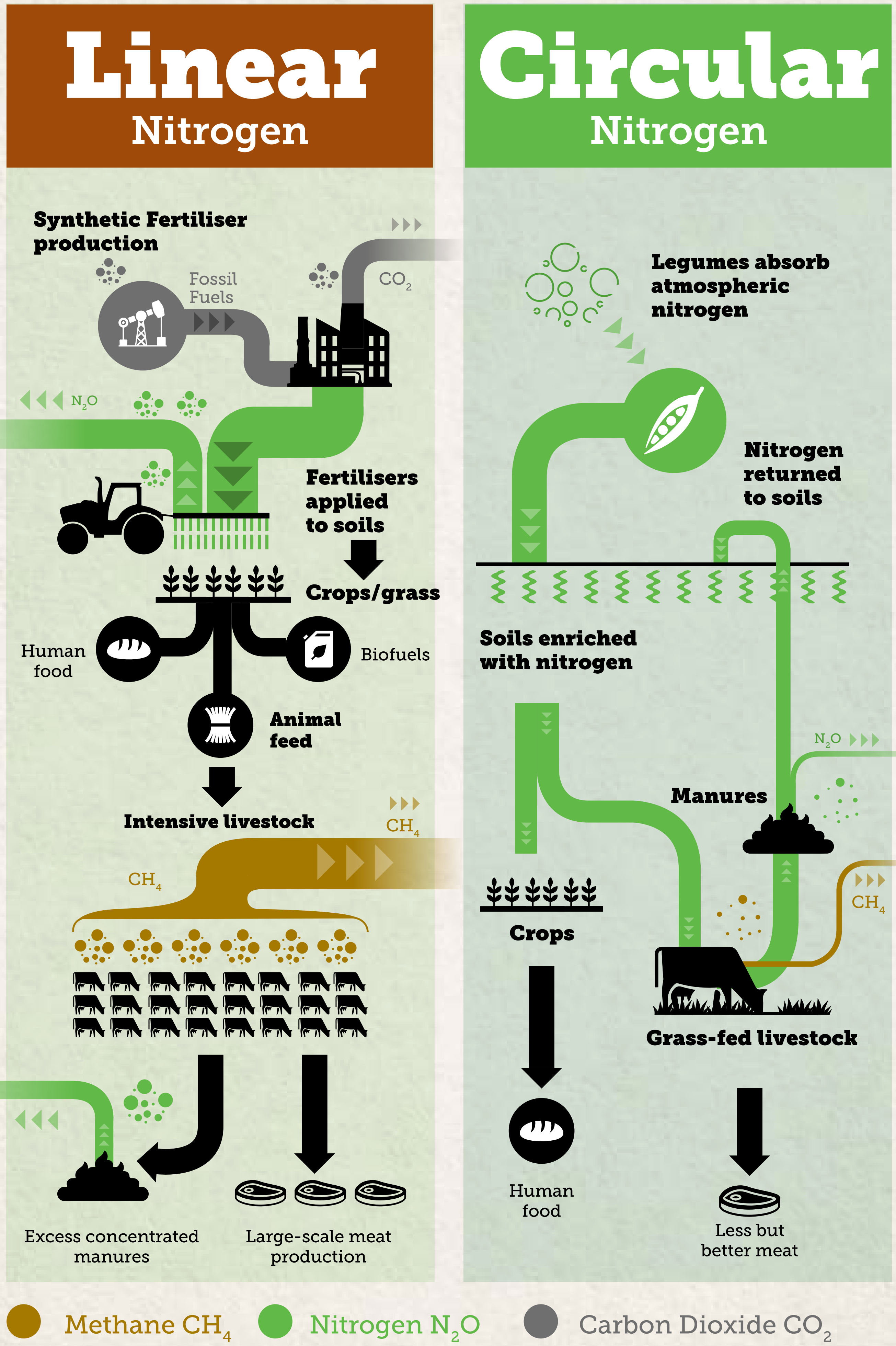
systems and biofuel production, rather than supporting the production of nutritious crops for direct human consumption.

Solutions to the nitrogen challenge need to come at multiple levels:

- **At international level** nitrous oxide emissions need much greater attention in global greenhouse gas accounting. Methane emissions must be reduced, but it has received disproportionate attention while nitrous oxide has been overlooked. This is due in part to a historical underestimation of its true contribution to global warming.
- **At national level** opportunities must be taken to join the dots by tackling excess nitrogen as a climate, nature and health issue in an integrated way.
- **At farm level** support is needed to incentivise, plan and regulate farm practices to manage nitrogen more efficiently. More research is needed to understand and address nitrogen losses from all farming systems, including the interaction of nitrogen and carbon in soils, and potential ways to reduce losses to the environment from biological nitrogen fixation and in the application of manures.

The underlying urgent issue remains the need to dramatically reduce the quantity of reactive nitrogen being released into the environment through the creation of synthetic fertilisers. Agroecology presents a practical route forward, promoting practices which cycle nutrients through animal manures and nitrogen fixing crops and avoid synthetic fertilisers. The Ten Years for Agroecology model by IDDRI suggests how this could be achieved at the European scale whilst still producing sufficient food for the population, eliminating the diversion of crops for animal feed and biofuels and maximising grassland utilisation.

Major disruptive events have highlighted the vulnerable nature of food and farming supplies. Governments have shown they are prepared to make rapid interventions on food access, availability and distribution. This should be taken as a signal that it is politically possible to intervene in transitioning towards sustainable and resilient farm systems. A key component of that transition is to fix the broken nitrogen cycle. To tackle climate change, protect ecosystems and enhance human health, we must act fast to close nutrient loops and reduce nitrogen input.



Linear
Nitrogen
Synthetic Fertiliser production
Fossil Fuels
CO2
N2O
Fertilisers applied to soils
Crops/grass
Human food
Biofuels
Animal feed
Intensive livestock
CH4
CH4
Excess concentrated manures
Large-scale meat production
Circular
Nitrogen
Legumes absorb atmospheric nitrogen
Nitrogen returned to soils
Soils enriched with nitrogen
N2O
Manures
CH4
Crops
Grass-fed livestock
Human food
Less but better meat
Methane CH4
Nitrogen N2O
Carbon Dioxide CO2

Too much of a good thing

Nitrogen is found in all living things. It is essential for all food and farming systems. Historically, farmers would grow a natural nitrogen-fixing crop like beans for a year before growing cereal crops. This practice was at the core of maintaining crop fertility alongside the use of animal manures. However, this has meant that available nitrogen was a limiting factor in some farming systems.

At the start of the 20th Century, German chemists Fritz Haber and Carl Bosch developed a commercial method to artificially fix atmospheric nitrogen into a useable – reactive – form. The Haber-Bosch process uses methane (normally derived from natural gas) to convert nitrogen and hydrogen to liquid ammonia, which is the core ingredient of synthetic fertilisers. It is now clear that this process has enabled a huge increase in reactive nitrogen in the environment with unintended consequences.

The creation of synthetic fertilisers has been the backbone of agricultural intensification across the world, boosting yields and feeding a growing human population. Today, most people around the world are fed via synthetic nitrogen sources.

Synthetic fertilisers have been the single greatest addition to the overall levels of reactive nitrogen circulating in soils, water and the atmosphere.[1] In Europe more than half of all man-made reactive nitrogen derives from synthetic fertilisers. That is more than all industry, traffic, imported food and crop fixation combined.[2] The result of all this creation of new reactive nitrogen is a doubling of the global cycling of nitrogen within the past century.[3] One of the impacts of this surge in reactive nitrogen, only recently appreciated, has been increased emissions of nitrous oxide – a greenhouse gas with significant global warming potential – which is released during the use and breakdown of reactive nitrogen.

Nitrogen in many forms:

Dinitrogen (N_2) is the inert or unreactive form of nitrogen. It is the most abundant element in our atmosphere making up 78% of air we breathe, and it makes the sky blue. Fixing dinitrogen into reactive forms is the basis of life as we know it.

Ammonia (NH_3) is the primary form of reduced nitrogen and core ingredient in synthetic fertiliser production. Known for its strong smell, it contributes the primary air pollutant from farming. When it bonds with airborne particulate matter (PM) it can have serious public health impacts.

Nitrates (NO_3^-) are the main soluble form of nitrogen in water. Excess reactive nitrogen leaches from soils, sewage or airborne deposits, forming nitrates in water. As a water contaminant it affects human health and causes eutrophication of ecosystems threatening biodiversity.

Nitrous oxide (N_2O) is a powerful greenhouse gas that contributes to global warming. Food and farming are estimated to contribute more than half all human-induced nitrous oxide emissions. It is now the main cause of stratospheric ozone depletion.

This report looks in more detail at the contribution of excess nitrogen to climate change, as well as the better-known impacts on the natural environment, and on public health. We conclude that tackling excess nitrogen must be done at global, national and farm levels, to transition away from a century of activating too much nitrogen for the planet to cope with. Moving to a food future that works for climate, nature and health that is less dependent on synthetic nitrogen is essential, and radically different approaches will be needed to realise that ambition.

Nitrogen fertiliser - the overlooked driver of climate change

Nitrogen fertilisers contribute to climate change in two major ways. Firstly, from fossil fuel reliant manufacture and, secondly, greenhouse gas emissions from soils where they are applied. They emit the powerful greenhouse gas nitrous oxide, an overlooked driver of climate change and farming produces more of this gas than any other sector.

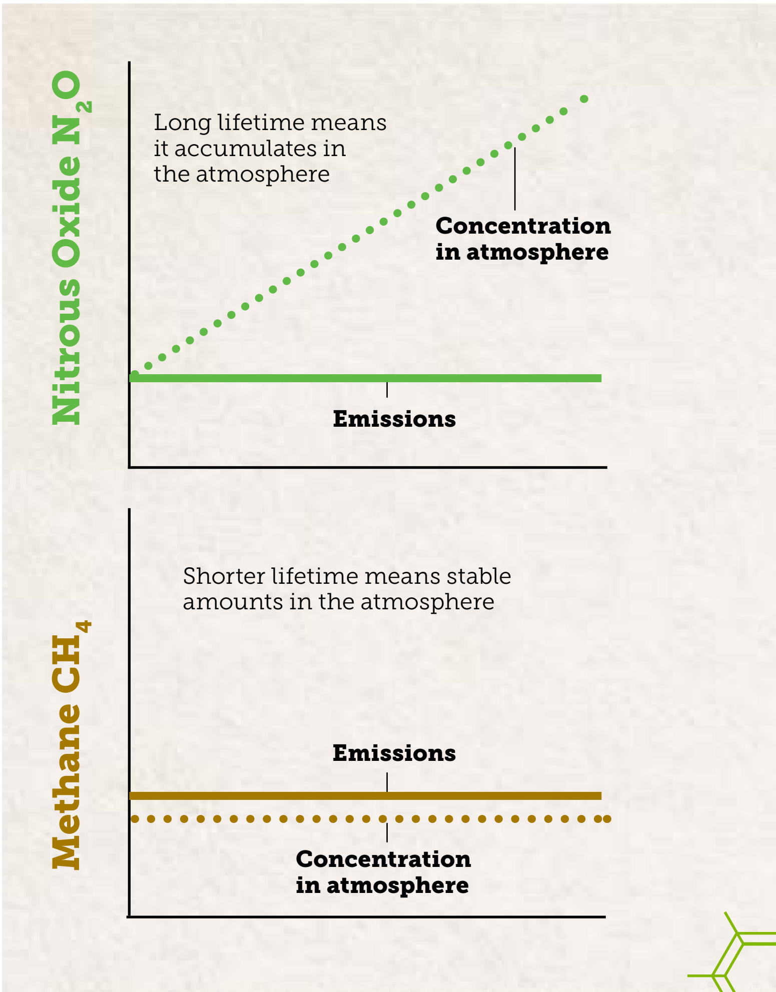
Different greenhouse gases have different impacts on the climate; there are both 'long-lived' and 'short-lived' greenhouse gases and they are of different potency.[4]

Nitrous oxide (or N_2O) is in the 'long-lived' category, persistent for an average of 114 years in the atmosphere and up to 300 times more potent than carbon dioxide.

Methane, by contrast is a 'short-lived' greenhouse gas, and though potent for a short period it is broken down on a timescale of around 12 years.

Until now, the focus on the climate impact of food and farming has been on other gases – carbon dioxide and most notably methane – and the issue of nitrogen has received much less attention.*

Recent research into nitrous oxide emissions suggests global climate modelling has underestimated its true contribution to global warming. Emissions may in fact be double what models assumed between 2000-2005 and 2010-2015.[5] Reducing the greenhouse gas emissions relating to nitrogen use in agriculture is therefore rising quickly up the climate agenda and requires a focus both on nitrogen fertiliser and nitrogen-rich animal feed.



* Beyond greenhouse gases there is the additional risk of nitrous oxide contributing to ozone depletion. The big ozone depleting gases hydrochlorofluorocarbons (HCFCs) have been successfully phased out globally through the UN Montreal Protocol, 1987. This is the big global climate success story, but nitrous oxide sits outside of this regulation and is on course to become the top ozone-damaging pollutant in the 21st Century.

Crops for animal feed use 80% of all nitrogen input in Europe

Greenhouse gas accounting

Greenhouse gases are, by their nature, global; they are everyone's problem. Yet in global accounting, emissions are factored on a territorial nation-state basis. The life-cycle emissions from imports ('consumption emissions') are not factored into UK accounts, but they make up 46% of the UK's total carbon footprint.[6] The UK ambition to reach net-zero by 2050 does not factor in consumption emissions. However, because the UK is reliant on imports of fruit, vegetables and animal feed, and their nitrogen footprint, the UK is dodging a large swathe of the embedded nitrous oxide emissions back down the production chain.

The impact of nitrogen fertiliser

Farming has always been dependent on the natural nitrogen cycle, creating and utilising reactive nitrogen and releasing nitrous oxide to the atmosphere. However, the ability to artificially fix nitrogen has hugely increased the amount of available reactive nitrogen created and this has underpinned a huge change in farming practice. This is clearly seen in arable farming, where modern varieties of wheat grown under intensive conditions provide extremely high yields but are hungry for nitrogen fertiliser. Intensive livestock systems drive high demand for these nitrogen-hungry wheat crops for animal feed. This in turn incentivises the overuse of fertilisers, which has a direct greenhouse gas impact. Globally, wheat crops use almost half the total nitrogen fertiliser applied. [7] A recent life-cycle analysis of a typical UK wheat-to-bread supply chain found that synthetic fertilisers account for more than 43% of the total global warming potential of a loaf of bread.[8]

The increased nitrogen load from farming contributes to nitrous oxide emissions via the soils where synthetic fertiliser is applied to boost crops for food, feed and fuel, and the emissions from manures generated by increasing livestock numbers. Most of this fertiliser is applied to crops, such as wheat, that are destined for animal feed. In Europe, animal feed accounts for 80% of all nitrogen inputs, largely in the form of synthetic fertiliser.[9]

Manure, once a valuable resource, is now a problematic waste product in the intensive livestock systems fed by fertiliser-boosted crops. The use of manure releases nitrous oxide as well as methane, which can both lead to greenhouse gas emissions during storage and processing. The highly concentrated numbers of livestock in these systems make managing manure complicated, expensive and risky.

Livestock, then, are the primary driver of nitrous oxide emissions from farming,* but they are not the only driver. Many arable crops are not solely destined for human or animal feed. An increasing portion are grown to produce energy. Biofuels are hungry for nitrogen fertilisers and the apparent global warming gains made by their replacement of fossil fuels in vehicles and industry could be undermined by an increase in nitrous oxide emissions from over-fertilised soils.[10]

Intensive livestock and the climate change challenge

The link between intensive livestock production and the increase in nitrous oxide emissions makes it clear that current levels of global meat consumption are unsustainable and will need to decline to tackle climate change. However, grass-fed ruminant livestock will continue to play a crucial role in making nitrogen available for crops in the form of manures, as part of the transition away from synthetic fertilisers. At the same time measures will be needed to reduce nitrous oxide emissions across all farming operations, addressing fertiliser application and reducing emissions from manures.[13] Consuming less but better produced meat, delinked from synthetic nitrogen, provides a pathway out of the excessive nitrogen use in high output intensive livestock systems.

Fertiliser manufacture: Fossil fuel lock-in

The production of synthetic nitrogen fertilisers relies on large volumes of fossil fuels, generally in the form of natural gas. Methane from the natural gas provides the raw material for fertiliser production as well as the energy source to run the energy-intensive Haber-Bosch process, which consumes 3 - 5% of total natural gas globally.[11] Since 2000, global ammonia production (from which synthetic nitrogen fertiliser is made) has increased by a third, meaning that synthetic fertiliser accounts for an estimated 145 million tonnes of use of ammonia annually.[12]

*In addition to the nitrous oxide impacts of animal feed production there is a high climate cost from carbon emissions associated with habitat clearance.

Excess nitrogen as a risk to nature

Plants need nitrogen, but in excess it undermines wildlife habitats and ecological functions. Global biodiversity assessments show excess nitrogen in the air and water as one of the most significant biodiversity threats.[14]

Much of the nitrogen applied to farmland is lost to the air and into rivers and streams, impacting the wider environment. Most UK semi-natural habitats require nitrogen levels to be low in order to function. Today, most of these habitats are overloaded with nitrogen deposited from the air, reducing wildlife diversity and damaging plant and soil health.[15]

When there is a surplus of nitrogen, some plants and fungi do better than others. Nitrogen-tolerant species such as nettles and hemlock thrive with these high nutrient levels to the detriment of more sensitive species, reducing wildlife diversity. The impact of excess nitrogen levels is being felt in protected habitats (such as marshes, bogs, meadows and woods) where nitrogen is not routinely applied but reaches habitats through atmospheric deposition. 95% of England's 'nitrogen-sensitive' protected habitats have exceeded the critical load for nitrogen, putting them at risk of significant harmful effects.[16]

Below-ground, soils suffer too. Excessive application of synthetic fertilisers has been shown to acidify soils – or reduce pH levels – with negative implications for soil fertility, resulting in nutrient deficiencies and yield reductions.[17]

Nitrogen impacts on aquatic life

Reactive nitrogen is soluble and therefore easily makes its way into and through water systems. Increased levels of nutrients in watercourses encourage plant growth, particularly those such as algae. These 'algal blooms' reduce light and oxygen levels in water, a process known as eutrophication, which alters plant communities, kills fish and has effects all the way up the marine and freshwater food chains. Key coastal habitats, such as the South China Sea and Gulf of Mexico, have been overwhelmed by huge algal blooms thousands of miles across. [18] In addition, fisherfolk whose livelihoods depend on these coastal habitats, find themselves in tension with farmers upstream whose activities can overload the watercourses with damaging nutrient loads.

In England only 16% of inland freshwater bodies are close to their natural state. Most of the pollution arises from phosphates and nitrates, largely from water companies or farms (which are the most highly monitored and regulated sectors). The ambition, set out in the UK Government's 25 year Environment Plan for England to return 75% of waters to near natural state – without firm targets on reducing total nitrogen input – may be unachievable. The Environment Agency's own assessment is that this ambition will take over 200 years to achieve under the current rates of progress.[19]

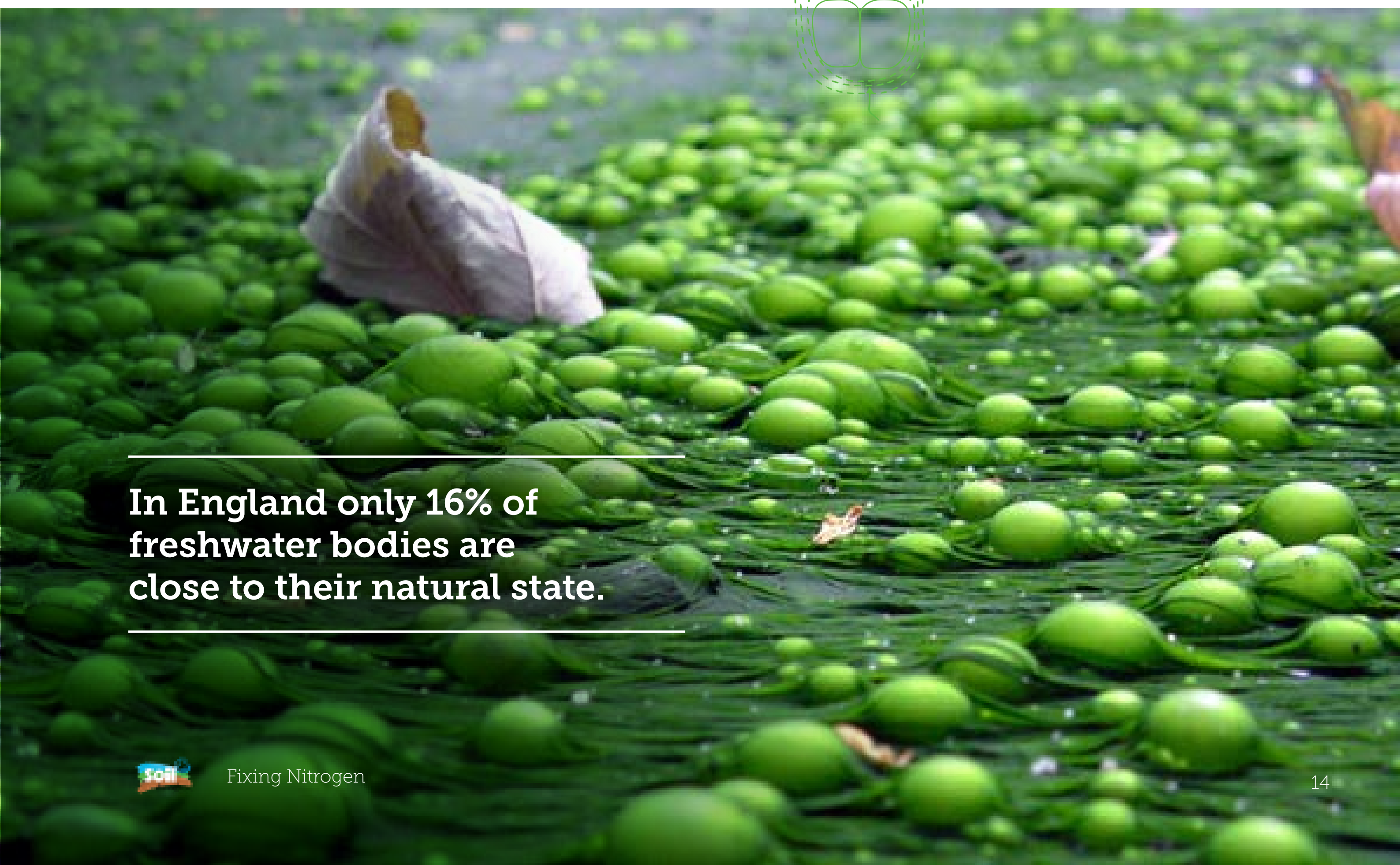
Fertiliser, intensification and farm wildlife decline

From plant breeding to soil structure, the abundant use of nitrogen fertilisers has been the lynchpin of agricultural intensification. This has created ecological imbalances and changed the nature of farming itself. Starting from the seed, the fast-growing high-yielding crops that fill most of the arable landscapes of Europe are dependent on synthetic fertiliser inputs. What was once a patchwork of diverse grains, plants and animals has been simplified to a handful of varieties and breeds. Modern grain crops grow tightly together and block light to the field floor, meaning that once abundant arable plants like cornflowers are on the verge of extinction, dropping 99% in 50 years.[20] The effects have had an equally dramatic impact on UK farmland birds, which have seen a 48% decline over the same period. [21]

Over-fertilised crops can be more vulnerable to pests and disease. Dense crops with less airflow makes them more susceptible to fungal infection. With high nitrogen application a plant's external barriers can be weaker and at greater risk of pest predation.[22] As a result, many farm systems are locked-in to using pesticides to exterminate pests, but which also harm non-target farmer-friends like bees and earthworms. Plants grown without synthetic fertilisers in organic systems produce metabolites as natural defences against pests. This has been shown to enhance antioxidant levels in food produced and evidence is growing on how these nutritional differences improve human health outcomes.[23]

Much as in protected habitats, nitrogen loving wild plants are prevalent across the farmed environment and one such plant, blackgrass, has become the bane of UK arable agriculture. Blackgrass has developed resistance to the herbicides used to control it, rendering some arable land unsuitable for certain crops.[24]

Intensification is not exclusive to arable crops; livestock farming has been increasingly pushed into nitrogen surplus. The process of 'improving pasture' has generally meant re-seeding grasses with more productive varieties that are less diverse, require higher fertiliser application, and support higher stocking densities. Whilst enabling greater production, growing more grass to feed more animals has put the conservation of many species at risk *(see case study 2 for more detail).*



© F. Lamiot / Wikimedia Commons

In England only 16% of freshwater bodies are close to their natural state.

Nitrogen deposition

Much of the nitrogen pollution affecting habitats happens through deposition of atmospheric nitrogen on to land. Ammonia, is deposited either through rain (wet deposition) or direct contact with other particles in the air (dry deposition). As a gas, ammonia knows no boundaries, and many of the areas worst affected by nitrogen deposition are non-target sites for fertilisers. Often in close proximity to intensive livestock units. Soils are at risk of acidification when excess nitrogen is deposited. In the UK, the reduction of sulphur deposition since regulatory controls changed industrial processes has meant soil acidification is today largely caused by nitrogen deposition from agriculture.

The nitrogen load from livestock

The intensification of livestock production has come with the tendency to geographically cluster livestock units. This has created two simultaneous nutrient management challenges: (i) inputs: large volumes of nutrients are imported to these regions as either feed or fertiliser; (ii) outputs: large volumes of manure and slurry are created, which cause direct pollution to air and water. They also generate waste that can exceed the nutrient absorption capacity of surrounding crop and pastureland. Without effective monitoring systems in place, and with such a localised nutrient burden, it is extremely challenging to control these nitrate excesses.[25]

Ruminant livestock play a major role in maintaining natural fertility through the manures they produce. But in intensive livestock systems, animal manure, once viewed as a resource, has become a polluting waste product. In the UK, regional concentration of intensive livestock systems has led to nitrogen pollution hotspots including Northern Ireland, England-Wales border counties and parts of the South West of England. Any map of English land use classification shows pasture in the West and arable in the East, leaving a yawning gap between where nutrients are concentrated and where they are needed. The separated practices of livestock and crop production need to be reconnected to a much greater degree to enable efficient nutrient utilisation.

Gaps in nitrogen regulation

The EU Nitrates Directive has regulated nitrogen loads at farm level since 1991. Yet since its implementation this regulation has failed to successfully curb nitrogen pollution across Europe: more than half of the European territory still exceeds critical levels of nitrogen.[26] Experience suggests there are significant difficulties in enforcing environmental regulations, particularly those relating to nutrients. Intervention to reduce the overall input of nitrogen may be the only practical way to address this challenge.

The specific environmental pressures created by clusters of intensive farming enterprise are not currently considered in regulation and permitting. Across the UK, permits for livestock units are given case-by-case, which overlooks the water pollution and nitrogen deposition created by clusters of livestock units within catchments *(see case study 1)*.

In England, the planning and enforcement regimes that may have controlled this expansion have been scaled back dramatically in recent years. The Environment Agency's environmental protection budget fell by 62% between 2010 and 2016, with a third fewer water course inspections and an 80% fall in prosecutions for breaches of the law.[27]

As well as assessing the impacts of geographical clusters on nitrogen pollution, there is a clear need to move away from monitoring and enforcing soil, air and water pollution in silos, and instead to address them in unison.[28]

The specific environmental pressures created by clusters of intensive farming enterprise are not currently considered in regulation

Case Study 1: Livestock ammonia pollution damaging ancient woodlands

Nitrogen deposition is one of the greatest threats to ancient woodland in the UK, with ammonia emissions from intensive livestock production a significant environmental risk in many rural areas. Ancient woodlands, such as Coed y Gopa in North Wales, have developed over hundreds of years with very low nutrient levels, but this woodland, which is in close proximity to an intensive poultry unit now has a high background ammonia concentration of 1.5 µg-NH_3/m^3.

Lichens are highly sensitive to air pollution and are a good indication of the overall health of a wood. A survey at Coed y Gopa found that nitrogen-sensitive lichens, characteristic of this type of habitat, were very scarce, while nitrogen-tolerant species were abundant.[29] In some parts of the wood, all lichens were scarce, and branches and twigs were found to have a covering of green algae, which is also indicative of high levels of nitrogen pollution. The impact of increasing levels of nitrogen pollution can, over time, significantly alter the overall ecosystem functioning of the entire habitat: for example, as nitrogen-tolerant plants out-compete other species. In Coed y Gopa, flora such as stinking hellebore and wild thyme are vulnerable, as are invertebrates like the dingy skipper butterfly, which requires larval food plants that occur on infertile soils.

In comparison, Coed Dolifor – another ancient woodland in Wales – has much lower ammonia levels at around 0.9µg-NH_3/m^3. A survey found a high abundance and diversity of nitrogen-sensitive species, with nitrogen-tolerant species largely absent.[30] However, a proposed intensive poultry unit 100 metres from Coed Dolifor means that this ancient ecosystem is under threat.

A range of sources contribute to the total nitrogen deposition and ammonia concentrations at any location. These include emissions from transport, industry and unregulated agricultural practices.

Intensive agricultural developments can have significant local impacts, especially when smaller developments (<40,000 poultry birds) are proposed. This is because environmental permitting regulations do not apply to small units, so they are only considered as part of planning. However, the combined ammonia emissions from numerous smaller developments can add up to significantly higher levels and have a detrimental impact on local habitats, including woodland.

Some studies suggest that ecologically significant changes to ancient woodland occur at much lower levels than the currently accepted critical level of 1µg-NH_3/m^3.[31] Planning policies require that there is no deterioration of irreplaceable habitats, including ancient woodlands, yet many authorities (including the Environment Agency and Natural Resources Wales) still allow individual developments which collectively contribute 100% towards the level at which an ancient woodland ecosystem is considered to deteriorate.

With ancient woodland covering just 2.4% of the UK, it is vital that we protect what remains of this precious and vulnerable habitat. In most ancient woodland, nitrogen deposition and atmospheric ammonia concentrations already well exceed the levels at which woodland ecosystems, and their epiphytic lichen communities, begin to deteriorate.

© Alastair Hotchkiss/WTML

© Phillip Formby / WTML

(Left) nitrogen sensitive lichen Usnea florida, Coed Dolifor. (Right) freeliving algae on bare twigs, Coed y Gopa.

Case Study 2:
Putting wildflower meadows back into the farmed environment

Almost three-quarters of land in the UK is farmed, so making sure there is space for nature on farms is essential. However, intensification of farming practices has overloaded much of the land with nitrogen, eliminating 97% of wildflower meadows since the 1940s and depleting plants, fungi, soil life along with the insects, birds and mammals that depend on them.[32]

Some of our most botanically rich habitats are wildflower meadows where no fertilisers or pesticides have been applied. A healthy wildflower meadow can play home to a concentrated and unique diversity of flowers – sometimes more than 140 species. Nearly 1,400 species of pollinators and other insects rely on meadow plants for their survival.

Meadows (and their wildlife) have evolved over centuries as part of the traditional mixed farm, used for grazing and hay cutting. Unlike many other wildlife habitats, they are also, by definition, productive farmland and their future depends on pasture-fed livestock farming.

Wildflower meadows are a low nitrogen ecosystem and only need the nutrients recycled from grazing animal manures. Most plants cannot tolerate synthetic fertilisers or high levels of nitrogen pollution from the air or water; exceeding the 'critical load' for nitrogen deposition can cause species loss and habitat degradation, such as by stimulating growth of tall grasses that overshadow and out-compete more sensitive wild plants and fungi.

The intensification of farming during and after the Second World War was the major driver of the loss of 97% of wildflower meadows. Millions of hectares of semi-natural grasslands were ploughed up to grow crops, while almost the entire remaining area of permanent pasture was 'improved' with synthetic fertilisers.

From the 1980s peak, average nitrogen application to grassland (organic and inorganic) dropped by more than 50% to 52 kg/ha by 2008 and has plateaued since then.[33] Yet even these lower levels of fertiliser application make the soil too rich in nitrogen for most wild plants and fungi to survive. Of the remaining meadows, 75% occur in small fragments and remain vulnerable to destruction. More broadly, species-rich grasslands now constitute only a paltry 2% of the UK land area.

This excess nitrogen creates the luminous green pastures to which we have become accustomed in the landscape. Though they are productive and look healthy, the downside is that they are wildlife deserts, with diverse species crowded out by the grasses that thrive. This unsustainable demand for grass is driven by the high stocking densities, demand for high silage returns and intensive grazing we see today on many farms.

Large-scale restoration of meadows and other species-rich grassland is a huge opportunity to reduce nitrogen pollution and to tackle the climate, health and nature crises. In efforts to deliver nature-based solutions alongside sustainable food production, species-rich grasslands offer an opportunity not to be missed.

Joan's Hill Farm © Joe Costley-Plantlife


The impact of nitrogen on public health

Nitrogen pollution is a major contributor to ill health and mortality globally, shortening millions of lives. Emissions from diesel vehicles and industry, along with intensive farming are poisoning the air we breathe and the water we drink. Tackling this must bring together all sectors, unite cities and rural areas and reach across international boundaries.

Nitrogen excess has adverse impacts on human health including on lung function and growth, respiratory problems, asthma prevalence and incidence, cancer, heart disease and adverse birth outcomes.[34,35] Air pollution cuts short an estimated 40,000 lives across the UK annually, with a huge annual cost of up to £20 billion.[36] Most of these deaths are caused by exposure to nitrogen dioxides, which generally originate from transport combustion engines, primarily diesel cars. However, agricultural emissions are an important contributing factor to the health impacts of air pollution.

Agricultural ammonia and air pollution

In the UK, most ammonia pollution (87%) originates from farming. It is the only air pollutant that is on the rise, and the public health implications from ammonia exposure are yet to be taken seriously.[37] A recent analysis modelled how halving agricultural emissions could prevent 52,000 deaths a year in Europe, 19% of all mortality attributable to air pollution.[38]

When ammonia bonds with nitrogen oxides and sulphur dioxide from industry and transport it creates particulate matter (PM), a damaging air pollutant. In this form ammonia pollutants can travel far and wide. The London smog of 2014 is just one example. Originally attributed to the natural phenomena of Saharan Dust, further research found most of the PM pollutants originated from ammonia emissions from Northern European agriculture.[39] Mainland European farming pollutes the UK and vice versa, so it must be tackled at the international as well as the national level.

In the UK, most ammonia emissions arise from livestock: 47% from cattle, 15% poultry and 8% pigs.[40] Cattle are often assumed to spend their lives out on grass but this picture is rapidly shifting, as seen in the growth of large dairy herds. Government figures (1996-2017) show a near doubling in average herd size – from 74 to 146 cattle over that period.[41] Many of these cattle spend the majority of their lives indoors, with figures from 2012 suggesting that 16% of dairy cattle are permanently housed. This number is likely to be far greater today.[42]

Intensive livestock units, despite attempts at mitigation, tend to increase ammonia emissions due to high stocking densities, large volumes of slurry and impermeable surfaces.[43] For cattle and pigs the floor in these systems is largely slatted, often feeding huge slurry pits that require high capital investment and onerous ongoing management. The use of straw bedding has been found to act as an emission barrier, absorbing ammonium nitrates from livestock urine. This is backed up by government research, which shows straw-based systems have lower air pollution emissions than slurry-based ones.[44] Interventions, such as the UK Clean Air Strategy,[45] are making some welcome steps on air pollution, particularly in urban

© Angela Glienicke / Greenpeace

areas, but little attention has been given to the rural communities exposed to high localised ammonia emissions and often overpowered by the stench.[46]

In addition to ammonia, the emissions of bioaerosols (bacterial and fungal spores) from intensive livestock manure and slurry can have significant localised air pollution impacts. This currently sits outside of regulation in England.[47]

The economic costs of removing nitrates from our water

Health scares such as 'blue-baby syndrome' in the 1980s – where it was perceived that high nitrate levels in water reduced the ability of bodies (particularly children's) to absorb oxygen – have led to public policies to control the use and deposition of nitrogen in the UK's water supply.

These policies, which set legal nitrate limits, have effectively ended this health risk, but as overall nitrate deposition has remained high, the costs and efforts to continuously remove it have been enormous.

Wessex Water, a water company operating in South West England, spent £12 million building a nitrate removal plant in the pollution hotspot of Poole Harbour. The energy costs of running a single plant are £1 million annually; costs that are passed back to its customers in water bills.[48] Water quality monitoring cost the Environment Agency £60.5 million in 2017/18, 88% of the total budget for water, air and soil monitoring in England.[49]

Current regulation to limit nitrate pollution may not be doing enough. The long-term impact of a half-century of overloading our landscapes with nitrogen fertiliser may not have yet been felt. Experts suggest that there is a 'time-bomb' of nitrate stored in UK geology, particularly chalk soils, where they predict it could take more than 60 years for nitrate levels to peak.[50] The health, ecological and climate implications of this nitrate store should be taken very seriously.

Reducing the total nitrogen burden on the water system is the solution, and farming has a big part to play.

Water companies are implementing incentive schemes to stem pollution at source by paying farmers to plant cover-crops and buffer strips that slow the flow of nutrients. [51] In doing so, they are managing a form of catchment-based nitrogen 'budget' which presents a new way of thinking about nutrient management within a region. However, this cannot be considered a solution to the broader pressures that lead farmers to over-apply nitrogen fertilisers.

Market measures such as this can only go so far; without effective government intervention and incentives the farm sector will not be able to transition to systems that require the input of less nitrogen overall.

Excess nitrogen creates luminous green pastures, though they look healthy they are in fact wildlife deserts.

Nitrogen: The big questions

Nitrogen fertiliser has helped provide abundant food – but at the same time has undermined the natural systems that sustain us, contributing to global warming and damaging human health.

Is there a way to feed ourselves adequately whilst reducing the amount of reactive nitrogen created in the process?

Here we offer some potential answers to the main challenges of reducing dependence on synthetic nitrogen and suggest areas for further research and exploration.

What happens to yields when nitrogen is reduced?

Nitrogen is often used in excess, and inputs can be dramatically reduced without any significant yield reductions. In China, it has been estimated that a 30-50% reduction in fertiliser use can be achieved without any negative impact on yields.[52] The Defra Soil Nutrient balance shows that in the UK almost half (45%) the nitrogen applied to farmland is surplus. [53] Much of this is lost to the environment. The UN Environment Programme's Colombo Declaration has recently established the global 'Halve Nitrogen Waste' campaign, highlighting the fact that improving nitrogen use efficiency not only supports climate, nature and health goals, but also saves $100 billion globally annually.[54] However, reducing these inputs is only the first step, after which farm systems would need to be reoriented to focus on recycling nutrients and on healthy soils.

Are there alternatives to synthetic nitrogen?

Farming has historically captured atmospheric nitrogen through 'biological fixation', using leguminous plants and utilising animal manures. Mixed farming systems today rely on legumes like clover and field beans to capture nitrogen as part of their rotation. However, the intensification of agriculture and rise of synthetic fertilisers over the past century is mirrored by the fall of biological crop fixation. European data estimates that natural nitrogen accounted for 80% of annual nitrogen input in 1900. In 2000 it was just 5%, and all the while total input has increased four-fold.[55]

Because farm practices that work to capture nitrogen through leguminous crops limit the total load of nitrogen that can be applied to a field, nitrogen is viewed as a valuable resource, too good to waste. Without the short-cuts of synthetic nitrogen inputs, agroecological systems rely on the health, quality and structure of soils to support crops. It is these healthy soils that absorb run-off, filter nutrients and have a higher volume and diversity of soil microorganisms to break down nutrients more effectively. Many of the practices inherent to agroecological farming, such as cover-cropping, are widely practiced as techniques to conserve nitrogen. It improves soil structure, protects soils from erosion and leguminous cover-crops like vetch can also fix inert nitrogen at the same time.[56]

Effective utilisation of animal manures is also key to efficient nitrogen use and is facilitated in mixed farming systems. The intensification and specialisation of farming systems have separated livestock and crops, and the geographical clustering of these systems leaves multiple nutrient management challenges.[57] Areas of intensive livestock production depend on high fertiliser and feed inputs and create large volumes of manure and slurry, often impacting surrounding areas with nitrogen pollution. Meanwhile areas specialising in crop production have challenges accessing animal-based nutrient sources due to large distances, increasing the incentive to resort to synthetic fertiliser input. Global nitrogen flows such as through the import of protein crops for animal feed (e.g. soy from South America to Europe) create similar problems of nutrient transfer at a macro-level, enabling the intensive livestock units that generate local excess nitrogen.

Legislative approaches to encourage a shift away from synthetic nitrogen include the EU Fertilisers Directive, which will operate alongside the Circular Economy Directive and the recent Farm to Fork Strategy. These policies incentivise a shift to recycled nutrients and reduced reliance on imports and fossil fuels, while reducing the associated contaminants and heavy metals present in many synthetic fertilisers.[58]

Research shows that the population of Europe can be fed without synthetic nitrogen use

Can soil health be maintained with less nitrogen?

Yes; in fact too much nitrogen damages soil health. Inputs of synthetic nitrogen are not essential for soil fertility and in practice their use tends to undermine long term soil health. Functioning soil is an essential part of making nutrition available to plants. Reliance on synthetic fertilisers often leads to a reduced focus on healthy soil ecosystems that nourish crops, with knock-on consequences for soil health, structure and resilience to erosion, as well as biodiversity and greenhouse gases. This trend has had grave consequences for soil health: Defra analysis shows most arable soils in the UK have lost 40-60% of organic matter, washing away fertility and crucial soil carbon stocks.[59]

Though synthetic fertilisers may give an immediate productivity bounce, new studies highlight the depth of negative effects they have on soils, altering their complex communities of microbes, slowing decomposition rates, reducing available nutrients and ultimately stunting plant growth.[60] Nitrogen is required to maintain soil fertility, but its balance with other elements is critical. Carbon and

nitrogen are in a fine balance in soils; getting this balance right has significant implications for soil emissions, health and crop yields. Despite huge leaps forward in soil science in recent years, there is still a significant gap in understanding the dynamics of nitrogen in soils.[61]

Do diets need to change in a world with less nitrogen?

Adequate food production within planetary boundaries is clearly an overriding priority.[62] Yet, even with current excessive nitrogen use, millions of people are malnourished. The intention to increase food production for a growing global population needs to recognise planetary boundaries and the challenge of nutrient supply in nitrogen-scarce regions.*, [63] Facing this global context of constrained nitrogen, fairer distribution is essential.

In any future farming scenario – including a lower nitrogen one – significant diet change will be necessary. Modelling suggests that, in Europe, feeding a growing population a sufficient diet is possible without the need for synthetic nitrogen.[64] High meat consumption diets are by their nature nitrogen intensive; livestock are overall poor nitrogen converters. In these cases, eating 'less but better meat' and dairy is one clear way to affect rapid change. Even just applying nationally recommended healthy diets – e.g. the UK NHS Eatwell Diet[65] – across populations would enable farming to reduce nitrogen (and phosphorous) application by 10-15%.[66]

Diets currently reliant on meat and dairy from intensive livestock systems will need to shift to lower output extensive, outdoor and pasture-based livestock sources. Models such as the 'livestock on leftovers' approach – that uses non-human edible crops and residues to supplement animal nutrition – are an integral element of a closed-loop food system. They should be deployed to supplement these extensive livestock systems.[67]

All this implies drastically reducing the reliance on commodity crops for animal feed and repurposing arable animal feed crops for direct human consumption; significant reductions in pig and poultry production would follow.

*Many areas of the world (e.g. sub-Saharan Africa) have a serious nitrogen deficit with implications for farm productivity. Increasing the availability of reactive nitrogen in these regions is essential to address world hunger and maintain productive soils, and this can be achieved with minimal negative impacts on climate, nature and health.

The way through the nitrogen challenge

First, there must be recognition that nitrous oxide emissions have been seriously overlooked in global climate change mitigation models, whilst possibly excessive attention has gone to methane.

On the international level, greenhouse gas accounting needs to include the full climate impact of synthetic fertilisers, and the imported food and feed that rely on them in order to inform national policy making. This will undoubtedly necessitate a fundamental reduction in the amount of reactive nitrogen that is continually being added to the global environment. Nitrogen must be a key focus at the global climate summit, COP26, where there is a clear opportunity for UK leadership.

At national level, because nitrogen impacts are so wide-ranging across climate, nature and health, policy and legislative responses have tended to be compartmentalised across air quality, environment, agriculture and climate objectives. Whilst this is inevitable, an overview is needed to realise synergies between approaches to the different impacts. Building on experience of controlling emissions from the industrial sector, sustainable nutrient limits need to be set within catchments and permitting, and planning regulations and advice targeted accordingly.

At farm level, there is a need to incentivise, plan and regulate farm practices for nitrogen to reduce impacts in the most efficient way and secure win-wins. Most of the farm practice solutions to reduce nitrogen pollution are good for farm business efficiency as well as for nature, health and climate. Some of these actions are likely to be fairly generic across farms (for example good slurry storage) whilst others will be highly specific, such as maintenance and restoration of species-rich grasslands by targeted reductions in inputs. Overall, empowering farmers to innovate solutions, reduce their reliance on high fertiliser application, and transition to alternative farm systems is an opportunity for, and responsibility of, government.

System-level change – a transition to agroecology?

If nitrogen is an issue that needs to be tackled across multiple policy areas, are there joined up approaches that can deliver? One possible approach is agroecology, which at its core is a farming system that works with natural processes to produce food, fuel and fibre, positioning a farm system within natural cycles, including the nitrogen cycle.

Agroecology is a systemic approach that can help tackle the nitrogen challenges we face. A recent model by the think-tank IDDRI has laid out the pathway for Europe to become agroecological by 2050.[68] As a systemic approach to the challenges above, it shows how agroecological food and farm systems can facilitate:

- **A sustainable healthy diet for all.** When viewed from a food system sustainability context – e.g. changing diets and reducing waste[69] – a healthy diet can be provided for a growing European population while remaining within planetary boundaries[70] for key risk areas such as nitrogen surplus.
- **A shift to circular approaches to nutrient flows**, meaning nitrogen and other key nutrients like phosphorous are treated as a resource too good to waste. A recent meta-study from North America shows that on average an organic farm system uses recycled nitrogen for 50-100% of total needs, while conventional systems are found to only recycle 10-30% of nitrogen and are dependent on synthetic fertiliser in most cases.[71]

- **Improved soil health for nature, climate and our long-term food security.** Soil science has raced ahead in recent years, and good soil stewardship is today underpinned by the practices of agroecological farming such as cover-cropping, agroforestry and crop rotations. Farm productivity benefits too; farmers have known for generations that boosting soil health and biodiversity can increase crop yields.[72]

Food and farming supplies in the UK have been shown to be vulnerable to external shocks. Our lack of emphasis on domestic food supply should be viewed as a food security concern. More so, the reliance on fossil fuel imports for synthetic fertiliser input leaves us not only undermining net-zero climate commitments, but vulnerable to geopolitical and market shifts.

Agroecological approaches offer resilient alternatives to the status quo by closing these nutrient loops and reducing loss and input requirements. These options are essential in a resource constrained world.

We have recently seen that governments are prepared to intervene on food access, availability and distribution. This enthusiasm should be harnessed to transition to healthier diets that support more sustainable and resilient farming systems as part of getting to grips with the nitrogen challenge.

References

1 Liu, J. et al. 2016. 'Reducing human nitrogen use for food production'. **Sci. Rep. 6, 30104**.

2 Sutton, M. et al. (eds.) 2011. **The European Nitrogen Assessment: Sources, Effects and Policy Perspectives.** Cambridge: Cambridge University Press.

3 Fowler, D. et al. 2013. 'The global nitrogen cycle in the twenty-first century'. **Phil. Trans. Royal Soc. B. 368, 1621.**

4 Allen, M. et al. 2018. 'A solution to the misrepresentations of CO2 - equivalent emissions of short-lived climate pollutants under ambitious mitigation'. **Clim. Atmos. Sci. 1, 16.**

5 Thompson, R. et al. 2019. 'Acceleration of global N2O emissions seen from two decades of atmospheric inversion'. **Nat. Clim. Chan. 9.**

6 WWF-UK, 2020. **Carbon Footprint: Exploring the UK's contribution to climate change.**

7 Zhang, X. et al. 2015 'Managing nitrogen for sustainable development'. **Nature, 528.**

8 Goucher, L. et al. 2017. 'The environmental impact of fertilizer embodied in a wheat-to-bread supply chain'. **Nat. Plants 3.**

9 Sutton, M. et al. (eds.) 2011 (As above)

10 Revell. L. et al. 2012. 'Impacts of the production and consumption of biofuels on stratospheric ozone'. **Geophys. Res. Lett. 39. 10.**

11 European Commission, 'Fertilisers in the EU: Prices, trade and use. **EU agricultural market briefs, 15 June 2019.**

12 International Fertilizer Association, **'World NH3 Statistics by region 2007-2018'** (Accessed 21/04/20)

13 Leach, A. et al. 2012. 'A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment updated'. **Env. Dev. 1.**

14 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) '**Models of drivers of biodiversity and ecosystem change'.** (Accessed 15/05/20)

15 Hayhow, D. et al. 2019. **State of nature 2019.**

16 Plantlife, 2017. W**e need to talk about nitrogen: The impact of atmospheric nitrogen deposition on the UK's wild flora and fungi.**

17 Francioli, D. et al. 2016. 'Mineral vs. organic amendments: Microbial community structure, activity and abundance of agriculturally relevant microbes are driven by long-term fertilization strategies.' **Fron. Microbio. 7.**

18 US Environmental Protection Agency, '**Northern Gulf of Mexico Hypoxic Zone**'. (Accessed 19/05/20)

19 Fox, P. '**Water is precious – taking action now will improve water quality for generations to come**', Environment Agency, 22 August 2019. (Accessed 10/03/20)

20 Plantlife, 2013. **England farmland report: And on that farm.**

21 Defra, 2019. **Wild bird populations in the UK, 1970 to 2018.**

22 Sun, Y. et al. 2020. 'Unravelling the roles of nitrogen nutrition in plant disease defences', **Int. J. Mol. Sci. 21, 2.**

23 Baranski, M. et al. 2014. 'Higher antioxidant and lower cadmium concentrations and lower incidence of pesticide residues in organically grown crops: a systematic literature review and meta-analyses', **Brit. J. Nutr. 112.**

24 Varah, A. et al. 2020. 'The costs of human-induced evolution in an agricultural system' **Nat. Sus. 3.**

25 Natural England, 2011. **Environmental impacts of land management (NERR030) chapter 6, Nutrient and pollution management – intensive livestock.**

26 Buckwell, A. and Nadeu, E. 2018. **What is the safe operating space for EU livestock? RISE Foundation, Brussels. p.36**

27 Unchecked UK, 2019. **The UK's enforcement gap.**

28 House of Commons Environmental Audit Committee, 2018.**UK progress on reducing nitrate pollution, Eleventh Report of Session 2017–19.**

29 Hotchkiss, A., Assessment of Nitrogen Air Pollution Impacts on Ancient Woodland – Coed y Gopa 06/02/2019. Unpublished Woodland Trust report, Grantham, UK.

30 Hotchkiss, A. 'Survey and assessment of ammonia impacts on lichen communities – Coed Dolifor 10/02/2018'. Unpublished Woodland Trust report, Grantham, UK.

31 Giordani et al. 2014. 'Detecting the nitrogen critical loads on European forests by means of epiphytic lichens. A signal-to-noise evaluation'. Forest Ecology and Management 311.

32 Plantlife, 2017. (As above)

33 Defra, 2019. **The British survey of fertiliser practice; Fertiliser use on farm crops for crop year 2018.**
34 House of Commons Environmental Audit Committee, 2018. (As above)
35 Brunekreef, B. & Holgate, T. 2002, 'Air pollution and health', **The Lancet, 360, 9341.**
36 House of Commons Environment, Food and Rural Affairs, Environmental Audit, Health and Social Care, and Transport Committees, 2019. **Improving air pollution.** Fourth Report of the Environment, Food and Rural Affairs Committee, Fourth Report of the Environmental Audit Committee, Third Report of the Health and Social Care Committee, and Second Report of the Transport Committee of Session 2017-19.
37 Guthrie, S. et al. 2018. 'Impact of ammonia emissions from agriculture on biodiversity: An evidence synthesis.' **The Royal Society.**
38 Pozzer, A. et al. 2017. 'Impact of agricultural emission reductions on fine-particulate matter and public health', **Atmos. Chem. Phys. 17.**
39 Vieno, M. et al. 2016. 'The UK particulate matter air pollution episode of March–April 2014: more than Saharan dust', **Env. Res. Lett, 11, 4.**
40 Defra, 2019. **Inventory of Ammonia Emissions from UK Agriculture 2017 – SCF0107.**
41 Agriculture & Horticulture Development Board Dairy, **'UK and EU cow numbers.'** (Accessed 12/01/20)
42 March, M. et al, 2014, 'Current trends in British dairy management regimens'. **J. Dairy Sci. 97. 12.**
43 Defra, 2011, Developing new ammonia emissions factors for modern livestock housing and manure management systems - AC0123. EVID4 Evidence project final report.
44 Defra, 2002. **Ammonia in the UK.**
45 Defra, 2018. **Clean Air Strategy.**
46 Davies, M. 'Conflict in the countryside: How intensive farms are dividing rural Britain', 21 July 2017, **The Bureau of Investigative Journalism.** (Accessed 10/03/20)
47 The Environment Agency, 2018. (As above)
48 House of Commons Environmental Audit Committee, 2018. (As above)
49 Sustainable Soils Alliance, 16 March 2020, **'Soil failure leaving public in dark over environment, scientists warn'** (Accessed 20/04/20)
50 House of Commons Environmental Audit Committee, 2018. (As above)
51 Wessex Water, **'Poole Harbour catchment initiative'.** (Accessed 27/02/20)
52 Good, A. and Beatty, P. 2011. 'Fertilizing Nature: A Tragedy of Excess in the Commons'. **PLoS. Biol. 9, 8.**
53 Defra, 2019. **Soil nutrient balances: Provisional estimates for 2018. 22 August 2019.**
54 Sutton, M. et al. 2019. Nitrogen - Grasping the Challenge. A Manifesto for Science-in-Action through the International Nitrogen Management System. Summary Report. Centre for Ecology & Hydrology, Edinburgh, UK.
55 Sutton, M. et al. (eds.) 2011. (as above)
56 Doring, T. et al. 2013. 'Using legume-based mixtures to enhance the nitrogen use efficiency and economic viability of cropping systems', **report for Agriculture and Horticulture Development Board, project 513 August 2013.**
57 Poux, X. and Aubert, P-M. 2018. 'An agroecological Europe in 2050: multifunctional agriculture for healthy eating. Findings from the Ten Years For Agroecology (TYFA) modelling exercise', **Iddri-AScA, Study N°09/18, Paris, France.**
58 Council of the European Union, **'EU adopts new rules on fertilisers'** (Accessed 02/02/20).
59 The Environment Agency, 2019. **The state of the environment: Soil.**
60 Carey, J. 2016. 'Crucial role of belowground biodiversity', **PNAS, 113, 28.**
61 Zhang, X. et al. 2015. 'Managing nitrogen for sustainable development'. **Nature, 528.**
62 Gerten, D. et al. 2020. 'Feeding ten billion people is possible within four terrestrial planetary boundaries', **Nat. Sus. 1.**
63 Houlton, B. et al. 2019. 'A world of co-benefits: Solving the global nitrogen challenge'. **Earth's Future. 7.**
64 Poux, X. and Aubert, P-M. 2018. (As above).
65 National Health Service, 2020. **'The Eatwell Guide'.** (Accessed 15/04/20)
66 Rust, N., et al. 2020. 'How to transition to reduced-meat diets that benefit people and the planet', **Sci. of Tot. Env. 718.**
67 RSA Food, Farming and Countryside Commission, 2019, **Our future in the land.**
68 Poux, X. and Aubert, P-M. 2018. (As above).
69 Muller, A. et al. 2017. 'Strategies for feeding the world more sustainably with organic agriculture', **Nat. Comm. 8.**
70 Gerten, D. et al. 2020. (As above).
71 Cattel Noll, L. et al. 2020. 'The nitrogen footprint of organic food in the United States'. **Env. Res. Lett. 15, 4.**
72 Bender, F. and van der Heijden, M. 2014. 'Soil biota enhance agricultural sustainability by improving crop yield, nutrient uptake and reducing nitrogen leaching losses' **J. App. Ecol. 52.**

Lead author: Sam Packer
For inquiries and contact: **policymail@soilassociation.org**

With special thanks to the generous support
of the Ashden Trust which made this work possible.

THE ASHDEN TRUST

To find out more visit:
www.soilassociation.org

Soil Association
Spear House, 51 Victoria Street, Bristol BS1 6AD
T 0117 314 5000
Registered charity no. 206862

Do you need this in an alternative format?
If you require this document in an alternative format,
please call **0117 314 5001**
or email **digitalteam@soilassociation.org**
to request a copy.