Report of the Nutrient Management Expert Group (NMEG)

Improving policy and practice for agricultural nutrient use and management

Date: May 2024

We are the Department for Environment, Food and Rural Affairs. We're responsible for improving and protecting the environment, growing the green economy, sustaining thriving rural communities and supporting our world-class food, farming and fishing industries.

We work closely with our 33 agencies and arm's length bodies on our ambition to make our air purer, our water cleaner, our land greener and our food more sustainable. Our mission is to restore and enhance the environment for the next generation, and to leave the environment in a better state than we found it.

This publication is available at www.gov.uk/government/publications

Any enquiries regarding this publication should be sent to us at:

nm.expertgroup@defra.gov.uk

www.gov.uk/defra

Contents

Executive summary

Reasons for commissioning NMEG

Mitigating and adapting to climate change and protecting environmental quality whilst meeting society's needs for food and other resources is one of the most pressing challenges facing humanity. Nutrient management plays a key role in ameliorating this crisis. Agriculture is a major contributor to Greenhouse Gas (GHG) emissions globally, but also a key sector that provides food, energy and interacts closely with the environment. Improving nutrient management offers major opportunities for enhancing soil health, improving water and air quality, protecting and enhancing biodiversity and managing resources sustainably. These wide-ranging issues overlap and may compete, so must be tackled through joined-up policy making and integrated action. Since NMEG was commissioned in 2020, the international energy crisis has roughly tripled fertiliser[1] prices, highlighting the urgency of taking action on economic as well as environmental grounds.

Pollution from agricultural nutrient management is a complex problem, to which there is no single easy solution. Crops need nutrients, whether from organic or inorganic sources. All inputs can in principle cause pollution through gaseous losses following application, contamination or nutrient imbalance in soil, leaching to water, or gaseous emissions from the different activities of resource management (such as storage, processing and manufacture). Addressing only one type of pollution (and from only one source) can easily cause the simultaneous increase of another type of pollution elsewhere in the system. No single nutrient or management method can prevent all losses of nutrients to the environment. Nevertheless, much improved nutrient management remains vital for sustainable agriculture in the UK.

In response to these challenges, NMEG was formed. The Clean Air Strategy 2019 set out to reduce emissions of ammonia (NH_3) against the 2005 baseline, with 8% by 2020 and 16% by 2030 (DEFRA, 2019). The strategy provided a comprehensive set of actions to improve air quality, improve public health, protect the environment and boost the economy. Included in these actions was a commitment to set up an expert group including agricultural policy experts, agronomists, scientists, and economists. The group should make recommendations on the optimal form of policy to minimise pollution from fertiliser use.

As links to other nutrient issues were quickly recognised, the remit of the planned group was expanded.

---

[1] 'Fertiliser' used in this report takes the broader meaning of any material applied with the intention of providing nutrients, or stimulating nutrient uptake or nutritional efficiency, to plants. This means it encompasses both organic materials like manures and slurries, as well as inorganic bagged fertilisers.

It was tasked with challenges such as:

- exploring the more efficient use of organic and inorganic nutrients
- limiting ammonia emissions
- reducing GHG emissions and water and soil pollution
- protecting and restoring sensitive habitats
- taking into account food production and the nutrient requirements of society

NMEG was launched in November 2020, to advise Defra on how to minimise pollution from the use, manufacture, storage and distribution of nutrients arising from agriculture and intended for crops. It met monthly and focused on specific questions provided by Defra on different policy themes in each meeting, inviting additional experts as appeared most relevant. It liaised regularly with a wider stakeholder group and sought to develop principles and recommendations for the specific themes and for the wider agri-food and land management systems within which they arise, aiming for a holistic view throughout.

This NMEG report aims to combine the considered advice of its members with insights from Defra's policy teams and single-element expert groups, providing a coherent approach to enhance nutrient management policy.

Key report outcomes

Nutrient management is a significant concern for the UK government and demands a co-ordinated, long-term and strategic approach that is adaptable and monitored effectively (**Recommendations 1, 2, 3, 4, 5 and 6)**. The significant challenge of meeting current and proposed future environmental targets will require wider change across the agri-food sector, and more radical shifts in practices of food production, supply and consumption. New policy measures will be required to match these high-level ambitions.

Application of the Farmscoper tool (a decision support tool for assessing farm mitigation measures to reduce diffuse pollution) to England and Wales found a reduction of nitrate, P, sediment, methane, nitrous oxide, and ammonia emissions by 20%. Further reductions would depend on the incorporation of additional measures, such as for ammonia where experience in Europe has shown 50% emission reduction is possible. This indicates the need for innovation, to embrace more ambitious interpretations of 'best practice' and improve technical performance, and for wider structural change which could lead to greater reductions **(Recommendation 2 and 10)**.

New policy approaches must be balanced with wider land use strategies, ensuring food, water and energy security are also considered so that shifts are sustainable for the long term. This is particularly evident in the current global situation of high natural gas prices, impacting on nutrient supplies for agriculture, energy markets and the cost of living (**Recommendations 3 and 11**).

The government should ensure public and private investment is increased to farming systems innovation, ensuring that a robust evidence base is available, and that mitigation and adaptation measures are supported. It is also critical that the correct advice and guidance is available to all, alongside robust accreditation schemes for advisors. Farm productivity for production of food, fibre and energy is critical, and responsible land managers should be supported to go beyond current levels. The government has a clear role and responsibility in this task (**Recommendations 12, 13, 14 and 15).**

The government should ensure future policies are meaningfully co-designed to ensure key stakeholders understand and embrace the targets, the pathways to reach them and how action should be monitored. Future policies should be communicated clearly and be adaptive to the wide range of landscapes, farming systems, environmental pressures and societal requirements that exist in the UK (**Recommendations 3, 8, 9 and 12**).

There is significant scope to ensure nutrients are used more efficiently on-farm: this requires better nutrient planning and monitoring on-farm, increasing responsible use of organic materials, reducing any excess nutrient inputs while also maintaining yield. It includes the application of a wide range of available technologies, many of which can save farmers money, but may have significant capital investment costs (**Recommendations 7, 9, 10 and 13)**. There are also opportunities for dietary and food system changes that could simultaneously promote healthier, balanced nutrition and reduce the environmental impacts of nutrient management by reducing nutrient use.

Recommendations

1. The farming community and its many partners have made important progress in better understanding and tackling nutrient pollution over the past 2 decades. However, given the scale of environmental issues at stake, current action remains insufficient to prevent significant further damage and Defra policies need to address this shortfall. A strategic, long-term approach is needed to encourage more effective nutrient management and much higher nutrient use efficiency on all farms, and across all landscapes. We recommend the development of a national Nutrient Management Strategy to achieve this.
2. Ambitious government targets for the environment must be supported by substantially increased public and private investment in innovation, mitigation and adaptation in the food system and sustainable land management, if they are to be realised. Many approaches require stronger support for capital investment, which can provide long term simultaneous rewards for efficiency, profitability and the environment.
3. Policy development through meaningful co-design is a proven approach for delivering positive change: farming, land management, food industry and other key stakeholders should be engaged throughout in agreeing a national Strategy and helping to promote the necessary sector shifts.
4. A coherent and effective suite of measures, combining regulatory change, incentives and opportunities for learning and innovation, is urgently required to meet the challenges that we face.
5. To deliver a strategy, a national nutrient management action plan is needed which is clear and coherent, based on evidence, and sets out the particular responsibilities of each main group of actors and institutions in working to achieve these goals. There are examples from other countries and in other topic areas of effective policies where the government, sector organisations and other key stakeholders work in close partnership to develop a strategy and action plan, overseeing how evidence is gathered and analysed and agreeing how best to organise the response: we commend this approach.
6. Among the critical resources that we have considered, soil is one in which the scientific knowledge base is still developing. Defra should consider setting new targets for specific services from the soil, as soil functioning is critical to reducing nutrient emissions to air and water, maintaining biodiversity above and below ground, and supporting plant production.
7. Defra should more strongly promote nutrient management planning as central to achieving greater nutrient use efficiency, and thereby reducing adverse environmental outcomes. There is scope for reducing nutrient input without a significant loss of yield, through improved nutrient management, to reduce the waste of valuable nutrient resources from farming systems.
8. Nutrient management policy should be flexible and adaptive to reflect the diversity of environmental conditions as well as farming systems throughout the UK.
9. Defra should establish a campaign in partnership with sector organisations to raise awareness of the substantial financial value of organic materials and nutrients

currently wasted, which can be reduced through improved planning and management. To better manage nutrient loadings, farmers should be encouraged by standards, advice and financial incentives to prioritise optimal use of organic materials such as manures and reduce excess inorganic fertiliser inputs.

10. Nutrient budgeting should be established as a basic standard for all farmers and land managers, and expectations applied appropriately to farms with different levels of nutrient loading and under different environmental conditions.
11. Notwithstanding the importance and urgency of achieving more ambitious nutrient management goals, we uphold the principle that policies should not unduly penalise continued farming and food production. Responsible farms must be enabled to stay in business so that they can meet these new goals by adapting their approaches, innovating, reducing waste and avoiding environmental harm.
12. This more joined-up and long-term, consistent policy approach to improving nutrient management needs to be communicated in a clear and accessible way. Policy should have a strong focus on recognising, supporting and extending farmers', land managers' and relevant supply chain actors' knowledge and skills, to achieve the necessary scale and pace of change to meet 25 Year Environment Plan targets.
13. Key guidance documentation and standards, notably the Nutrient Management Guide (RB209) published by the Agriculture and Horticulture Development Board, must be regularly updated to ensure they are authoritative and based on the full breadth of evidence emerging from practitioners, research and policy-makers.
14. A clear commitment must be given by government to ensuring that all farmers have access to high-quality, evidence-based and impartial advice, and support to help implement this advice, to reduce nutrient pollution from agriculture. A code of conduct and accreditation scheme such as Fertiliser Advisers Certification and Training (FACTS) or BASIS could be strengthened and widened, to help guarantee the quality, consistency and professionalism of advice from different providers. (BASIS is a charitable organisation committed to raising professional standards across land management and food production by supporting people and businesses with our industry leading qualifications, professional registers and auditing schemes.)
15. The government has a vital role to play in strengthening the evidence base for future policy development, and ensuring that standards and advice promote the public interest in effective nutrient management on farms. It must explicitly acknowledge this key role and the responsibilities that it brings.

Introduction

Nutrient management

Nutrient management is a term that encompasses the planning, storage, treatment, application and monitoring of nutrients for agricultural production. Plants require carbon, water and oxygen, and 13 other elements. While nitrogen (N), phosphorus (P) and potassium (K) are the elements required in largest quantities, a deficiency of any element can limit plant growth directly or indirectly via the uptake of other nutrients, reducing yield. In agricultural systems nutrients are taken away from the system with harvest and thus to sustain production, further nutrients must be added. Nutrient management therefore requires a delicate balance between supplying the nutrients needed for crop growth and avoiding excess nutrients that could be lost to the wider environment where they can damage ecosystems and contribute to climate change.

Plants obtain nutrients from several sources, and these must all be considered when planning nutrient requirements for particular crops:

- mineralisation of soil organic matter (all nutrients)
- deposition from the atmosphere (mainly N, but also P and S)
- weathering of soil minerals (P and K)
- biological N fixation by legumes (N)
- symbiotic associations between plant roots and mycorrhizal fungi (N and P)
- application of organic materials[2] (all nutrients)
- application of inorganic fertilisers[3] (all nutrients)

Nutrients are typically stored in soils and become available for plant uptake from within the soil solution (water held within the soil). Some plants can also take up nutrients via their leaves or from nodules in their root systems that host N-fixing bacteria. This means that to make best use of residual soil nutrients and nutrients applied to the soil, an understanding of the nutrient cycling is incredibly important. Balancing soil health and efficient nutrient management often go hand in hand.

---

[2] "Organic materials" in this report is used to define manures, green manures, slurries, digestate, biosolids, composts, ash, animal by-products or other materials of organic origin that are not geological deposits.

[3] "Inorganic fertiliser" in this report is used to define solid or liquid manufactured fertilisers that are produced through energy intensive production systems or are from mined non-renewable sources and typically sold in bags.

Despite the generally positive impact of nutrients on crop growth (quality and yield), inappropriate management can result in the loss of nutrients and other contaminants to the environment representing a waste of money for the producer.

Nutrients can be lost:

- to water through leaching, preferential flow, surface run-off in solution and attached to soil particles
- to air through ammonia volatilisation, and emissions of nitrous oxide and other forms of reactive N

Nutrient sources can also bring with them co-contaminants such as heavy metals which persist in soils for many years.

In England these losses currently present a significant flux to the environment, with one study reporting 70% of nitrate (just one component of the total N load in UK waters) and 25% of total P coming from agriculture as a national average. In rural catchments, the percentages of total N and total P in water that is delivered from agriculture are much higher. Such significant losses generate both local impacts on soils and water, and wider negative ecosystem and biodiversity impacts across the UK.

Nutrients are not just an agricultural input with an endpoint. They are broken down, transformed and recycled in many different interactions within the environment and the food system. Nutrient management is fundamental to the circular economy, where organic resources from different sectors need to be safely reduced, reused, and recycled wherever possible. Nutrients are also fundamental for a productive agricultural system that enables nutritious and sufficient food production. These interconnections make effective nutrient management policy-making and practice challenging.

Boundaries and definitions

The issue of pollution from nutrients is complex, spanning several sectors and policies. In the course of developing this report, NMEG focused on the use of nutrients from on-farm storage to land application. It did not directly explore nutrient content in livestock feed, neither did it have the remit to explore in detail issues relating to food security and human diets. Nevertheless, whilst these boundaries were set, the group discussed and identified linkages between and beyond specific themes, to achieve a more joined-up and coherent overview of the best ways forward.

The geographical and policy boundaries of NMEG discussions were focused mainly on England. Agriculture is a devolved area of policy and as such each nation of the UK has slightly different policy priorities and different agricultural landscapes. However, it did not mean that discussions only centred on England and that recommendations in this report would not be relevant for other nations to consider. Defra welcomed NMEG input and discussion of the ways in which other nations tackle similar issues.

Timeframe

In July 2020, applications were invited and promoted to a range of potential NMEG candidates, and selection processes were completed by October.

Meetings were held monthly online between November 2020 and December 2021. Selected additional experts were invited to join some group meetings to add their unique knowledge to the discussions. Themes were covered sequentially, in the following order:

Date	Discussion topic
December 2020 to January 2021	Air Quality
February to March 2021	Water Quality
April to May 2021	Net Zero
June to July 2021	Soils
August to September 2021	Circular Economy
October 2021	On-farm visit and cross-cutting issues
December 2021	Developing recommendations

A face to face on-farm meeting was held in the Autumn of 2021 to help the group scope its overall recommendations. Subsequent meetings in the first half of 2022 concentrated upon refining the recommendations through consultation with a wider stakeholder group and drafting this report with support of the Defra Secretariat.

The group was independent from government and this report should not be seen as government policy.

Membership

NMEG members are independent appointments made in line with Office of the Commissioner for Public Appointments (OCPA) guidelines on best practice for making public appointments.

Defra policy teams dealing with nutrients were involved throughout the process to put forward specific questions for debate, brief NMEG on background information and engage in discussions.

NMEG members were appointed from among farming, environmental and nutrient management experts, covering relevant areas of natural science (water, air, soil and climate), economics and behavioural science, and applied practical experience. Members work across England, Wales and Scotland, bringing insights from devolved administration schemes and contexts as well as English policy knowledge.

Chair: Professor Janet Dwyer, OBE (University of Gloucestershire)

Janet Dwyer is a policy analyst and developer with over 30 years' experience in applied rural research. Janet is Professor of Rural Policy at the Countryside and Community Research Institute, University of Gloucestershire. Her research expertise centres on European and UK agri-rural and environmental policy and practice. Alongside her role chairing the NMEG, Janet sits on advisory boards and panels for the Food, Farming and Countryside Commission, Green Alliance, Welsh government and Defra. She served as President of the UK Agricultural Economics Society, 2021 to 2022.

Professor Dave Chadwick (Bangor University)

Professor Dave Chadwick is a Professor of Sustainable Land Use Systems at the University of Bangor. His research interests and background are in the management of nutrients in livestock manures, fertilisers to optimise nutrient utilisation whilst minimising impacts on air and water quality. Dave is both an academic and involved in contributing to policy and practice.

Professor Jess Davies (University of Lancaster)

Professor Jess Davies is a Professor of Sustainability at Lancaster University. Jess uses her engineering background to create computer models that help us explore nutrient cycling in soils and their role in climate mitigation, water quality and food production. She has worked with a variety of global agri-food businesses, international NGOs and grassroot actors on valuing soil health.

Dr Vera Eory (Scotland's Rural College)

Dr Vera Eory is a Climate Change researcher at Scotland's Rural College. Vera has over fifteen years' experience working on the economic and environmental implications of GreenHouse Gas reduction practices in agriculture, advising government bodies and wider stakeholders. Her research also expands to the area of farmers' behaviour change.

Professor Alex Inman (University of Exeter)

Alex Inman is a Professor of Practice at the Land, Environment, Economics and Policy Institute at the University of Exeter. Alex is a practitioner and academic working within the field of natural resource management and exploring the interaction between agriculture and ecosystems. Alex is founder of the UK Farmer Discussion Group Network, stemming from his belief that farmers must be at the core of land use policy decision making.

Professor Penny Johnes (University of Bristol)

Professor Penny Johnes is a Professor of Biogeochemistry at the University of Bristol with over 30 years' experience researching the nature, origins, and ecological impacts of nutrient enrichment in freshwaters. She is Chair of the Defra Water Targets Expert Advisory Group, a member of its Biodiversity Targets Advisory Group, and of the Natural England Science Advisory Committee, and advises a range of other UK and international organisations on the nature and scale of nutrient enrichment impacts on inland and coastal waters, and strategies to mitigate these impacts.

James Price (Perdiswell Farm)

James Price is an arable farmer from Oxfordshire. with years of experience in managing arable systems. He is Chair of the Agricultural and Horticultural Development Board (AHDB) Crop Nutrient Management Partnership and has held numerous roles within the sector.

Professor Mark Sutton (UK Centre for Ecology and Hydrology)

Professor Mark Sutton is an environmental physicist primarily focused on developing an integrated approach to managing and communicating human alteration of the nitrogen cycle, with particular expertise in the emissions and behaviour of ammonia in the atmosphere. Mark has also developed tools for Defra and other government organisations to quantify the impacts of ammonia. He is a co-chair of the United Nations Economic Commission for Europe (UNECE) Task Force on Reactive Nitrogen, led the European Nitrogen Assessment and is currently leading the International Nitrogen Assessment in the UK.

Dr Rachel Thorman (ADAS)

Dr Rachel Thorman is a soil scientist at ADAS with over 20 years' experience of research in agricultural systems. Her work focuses on the management of livestock manures, other organic materials, and inorganic N fertiliser to optimise N utilisation whilst minimising diffuse pollution to the atmosphere and water. Rachel is leading the Defra project to submit UK N_2O and methane data to the Intergovernmental Panel for Climate Change (IPCC) Emission factor database.

Professor Sami Ullah (University of Birmingham)

Professor Sami Ullah is a Professor of Biogeochemistry at the University of Birmingham with over 20 years' experience in nutrient cycling. Sami's research primarily focuses on the biogeochemistry of N and its linkages to carbon and phosphorus cycling under global change in soils under agricultural and natural ecosystems. The impetus of his research is to advance mechanistic understanding of the response of key microbial functions such as denitrification, N and carbon mineralisation, biological N fixation, GHG fluxes and soil enzyme activity to land-use and climate change at catchment scale. This is fundamental for designing soil, land use and ecosystem management strategies, and predicting the future functioning of ecosystems under global change.

Professor Andy Whitmore (Rothamsted Research)

Professor Andrew Whitmore is a Soils and Agriculture Systems Modeller at Rothamsted Research. Andrew has over 35 years' experience as a modeller researching the carbon and N cycles and physical soil processes.

John Williams (ADAS)

John Williams is Head of Soils and Nutrients at ADAS. As a chartered soil scientist with over 30 years' experience, his research interests include the utilisation of organic materials, nutrient management and diffuse pollution mitigation. John is also FACTS qualified and provides strategic policy advice to government, levy bodies and water companies on soil and nutrient management.

Defra secretariat

NMEG's work was supported by a small team led initially by Dr Cecile Brich with support from Dale Connellan and succeeded by Dr Henry Webber. Team oversight was by Jane Learmount and William Brown. Final report was edited together by Dr Henry Webber and the Chair Professor Janet Dwyer.

Air quality

Defra briefing

Air pollution has a considerable impact on public health and the environment, due to increased morbidity rates and the damaging effects of pollutants on ecosystems, respectively (Manisalidis et al, 2020). In 2018, over 30,000 deaths were associated with particulate matter in the UK (Statista, 2022). Air pollutants such as ground level ozone (O_3) can damage plants and O_3 is estimated to reduce yields by 5% in arable crops in the UK (Mills et al, 2017). Atmospheric reactive N deposition can have severe impacts on N-sensitive habitats; in 2015 it was estimated that 80% of Special Areas of Conservation in England receive amounts of atmospheric N above their critical loads. The pressure of nutrient loading can lead to loss of species and irreversible change (Natural England, 2015).

Air pollution comes from many different sources, is present in many different forms and can have different geographical mobility and chemical transformations. Defra’s Clean Air Strategy identifies 5 harmful transboundary air pollutants for which the UK has adopted legally binding emission reduction targets:

1. fine particulate matter (PM2.5)
2. ammonia (NH_3)
3. nitrogen oxides (NO_x)
4. sulphur dioxide (SO_2)
5. non-methane volatile organic compounds (NMVOCs)

The most significant air pollutants as a result of crop nutrient management are ammonia (87% of emissions were from agriculture in 2020) and nitrous oxide (68% of emissions were from agriculture in 2019) (Defra, 2022a). Both NH_3 and NO_x contribute to the development of secondary fine particulate matter via chemical reactions in the atmosphere.

NH_3 can be released into the atmosphere through the volatilisation of N compounds but levels vary considerably depending on the quantity of N, its form and the surrounding environmental conditions (temperature, soil alkalinity, moisture). Agricultural NH_3 emissions come from the storage and application of manures and slurries from livestock, livestock housing, digestate, biosolids, deposition of urine and dung by grazing livestock, and from applications of inorganic fertiliser (Defra, 2019). By far the greatest contributors to agricultural NH_3 emissions in the UK are from beef and dairy cattle housing and manure management (see Table 1). The second largest contributor is the application of N fertilisers, particularly urea-based fertilisers (such as urea or urea-ammonium nitrate). The emission factors for different fertiliser types and manure, slurry and digestate are shown in Table 2 and 3. These factors are multiplied by the quantity of material or numbers of livestock and adjusted by other relevant factors (such as application method) to give an estimated total emission (Misselbrook and Gilhespy, 2022).

Table 1: Set of 3 tables adapted from Misselbrook and Gilhespy 2022, p.4 showing estimated emissions of NH_3 from UK agricultural sources in 2020 and sorted by management category.

Livestock source	Kt NH_3	% of total
Cattle (total)	115.3	51
Sheep	11.8	5
Pigs	15.9	7
Poultry	29.6	13
Minor livestock (horses on agricultural holdings, goats and deer)	1.3	1

Livestock source by management category	Kt NH_3	% of total
Grazing/outdoors	19.3	9
Housing	58.5	26
Hard standings	16.3	7
Manure storage	19.8	9
Manure application	57.5	25

Other sources	Kt NH_3	% of total
Fertiliser application	34.6	15
Sewage sludge application	4.7	2
Digestate application	15.3	7

There are several forms of oxidized nitrogen in the atmosphere. Nitrogen oxides (NO_x) are a mixture of nitric oxide (NO) and nitrogen dioxide (NO_2) and a key contributor to poor air quality. While most NO_x emissions in the UK result from combustion sources, nitrogen added to agricultural soils (as fertiliser and manures) also contributes. Nutrient management to reduce both NH_3 and NO_x emissions from agricultural sources could bring multiple benefits. As combustion source NO_x decreases through mitigation action in other sectors, soil NO_x is contributing an increasing share of total NO_x emissions.

Both NO_x and NH_3 contribute to the formation of fine particulate matter (PM2.5) as a significant risk to human health. By contrast, whilst nitrous oxide (N_2O) is a persistent gas that does not directly affect air quality for human health, it is a damaging GHG and one of the most important stratospheric ozone-depleting gases (Ravishankara et al., 2009). Like NO_x, N_2O emissions can occur directly from agricultural soils but this can be exacerbated by the use of inorganic fertiliser, cultivation of legumes in situations where this results in high levels of N in soils, ploughing in of crop residues, cultivation of histosols (organic soils), as well as storage and spreading of animal manures. The GHG significance of nitrous oxide is discussed in the Net Zero Chapter of this report.

The following indirect emissions pathways also lead to N_2O release into the air: atmospheric deposition of agricultural NO_x and NH_3 (which subsequently are converted to N_2O by soil microbes), reactive forms of N (Nr) (particularly NO_3 and NH_4); sediment /run-off containing N_r also results in N_2O production via nitrification and denitrification processes in receiving waters.

In the UK, air quality is currently governed by a mix of domestic legislation and international agreements. For agriculture specifically, several frameworks are in place to limit NH_3 emissions. Intensive pig and poultry farms are point sources of NH_3 emissions and all those over a certain size are regulated under the Environmental Permitting Regulations in England and Wales with equivalent legislation in Scotland and Northern Ireland. Farms with animal places for more than 40,000 birds, 2,000 pigs or 750 sows must hold an environmental permit which requires adoption of Best Available Techniques (BAT) in production processes to reduce emissions to air, water and land. BAT reduces emissions from these facilities by around 30% relative to preceding management practice practices at those sites (Misselbrook, 2022). Currently there is no national or international legislation on NO_x emissions from agricultural soils or manures.

Other policy and legislation not specifically focused on reducing air pollution but with co-benefits for it include Farming Rules for Water and the Nitrates Regulations, incentive schemes such as the Farming Investment Fund and Countryside Stewardship as well as guidance such as the Code of Good Agricultural Practice for Reducing Ammonia emissions (Defra, 2018a). These, together with on-farm advice offered through Catchment Sensitive Farming, are expected to help reduce agricultural NH_3 emissions and generate other co-benefits for emissions of N_2O by better managing total N loss (Environment Agency, 2019).

National planning policy underpinned by the Conservation of Habitats and Species Regulations, 2017, plays an important role protecting habitats sensitive to N deposition from NH_3 and NO_x emissions (from all sources) such as those coming from animal houses and manure stores. Planning permission may trigger the need for a ‘Habitats Regulations Assessment’ and can be refused or mitigation required if there is significant risk to such habitats.

Questions to NMEG

1. Is there any further evidence that could help support decisions on the optimal approach to reduce emissions of NH_3 from urea fertilisers that would achieve NH_3 emission reductions line with current targets?

2. Would improved nutrient management be effective in mitigating a shift away from urea fertilisers (to reduce ammonia emissions) considering the pollution trade-offs between ammonia and nitrous oxides?

3. What specific changes or additions are needed to measures relating to fertiliser (organic and inorganic) use to achieve the objectives set out in the Clean Air Strategy?

    a) To reduce NH_3 emissions from 2005 levels by 16% by 2030

    b) To reduce N deposition on sensitive habitats by 17% by 2030

    c) To reduce exposure to PM2.5

4. What approach should government take to spatial targeting of interventions to reduce NH_3 emissions from fertilisers?

NMEG discussion

Evidence on the reduction of NH_3 emissions from urea fertilisers

For NH_3, the UK emissions inventory estimates that emissions from ammonium nitrate (AN) are less than those from urea with urease inhibitors (see Table 1 and 2 for a comparison of different fertiliser types of emission factors). This means that complete avoidance of urea would reduce NH_3 emissions more than the use of urease inhibitors. In respect of reducing N_2O emissions as well as NH_3, Cowan et al. (2020) and Cardenas et al. (2019) provide evidence that different approaches may be required for grassland and for arable land. For arable, there is no significant difference in N_2O emission rates between urea and ammonium nitrate (or between urea with nitrification inhibitor and AN with nitrification inhibitor). For grassland however, experimental studies show lower N_2O emissions from urea than from AN, and from urea with nitrification inhibitor than AN with nitrification inhibitor. To reduce both N_2O and NH_3 on grassland, the best option could be urea with both urease and nitrification inhibitors (Freeman et al., 2020).

Work carried out in the GHG platform projects (AC0116 and AC0114) to improve the UK's agricultural GHG inventory showed that, other than N application rate, the main driver of N_2O emissions following ammonium nitrate (AN) application was rainfall. Most of the grassland happens to be situated in wetter areas of the UK. This means that it may be more helpful to frame discussion around rainfall zones rather than grassland and arable. There are areas of the UK where arable crops are grown in relatively high rainfall areas, and where grassland is located in lower rainfall areas. While noting the published evidence from Cowan et al. (2020) and Cardenas et al. (2019), this suggests that, for arable crops in high-rainfall areas, N_2O emissions might be expected to be less when using urea with inhibitors than from AN. Future policy choices related to type of N fertiliser therefore depend in part on the relative priority given to NH_3 or N_2O mitigation goals.

There is currently a lack of evidence on the effects of widespread use of urease inhibitors on soil microbiology and biogeochemical cycling, or on drinking water and freshwater. The conditions under which they have been marketed for safe and effective use in the UK may require closer scrutiny. Studies on freshwater, estuarine and marine environments indicate eutrophication effects from elevated urea concentrations (Gilbert et al., 2006). By increasing the lifetime of urea before its natural decomposition to NH_3, it might be expected that use of urease inhibitors could increase the opportunity for urea to enter watercourses.

Table 2 showing a range of Emissions Factors (EF) for nutrient types used on grassland from the Defra GHG Inventory for 2020, showing only direct emissions at point of spreading and as a percentage of the total N applied.

Fertiliser type	Ammonia EF (as % of total N)	Nitrous oxide EF (as % of total N)
Ammonium nitrate	1.69	0.94
Ammonium sulphate/Diammonium nitrate	2.64	0.99
Calcium ammonium nitrate	1.69	1.10
Other N and compounds	1.69	1.04
Urea	10.01	0.39
Urea Ammonium Nitrate	6.61	0.39
Cattle slurry	12.8	0.75
Cattle farmyard manure	6.48	0.33
Digestate from cattle slurry	18.03	0.75
Digestate from cattle farmyard manure	11.80	0.75
Digestate from food and crop materials	20.23	1.00

Table 3 showing a range of Emissions Factors (EF) for nutrient types applied to arable crops from the Defra GHG Inventory for 2020, showing only direct emissions at point of spreading and as a percentage of the total N applied.

Fertiliser type	Ammonia EF (as % of total N)	Nitrous oxide EF (as % of total N)
Ammonium nitrate	1.56	0.63
Ammonium sulphate/Diammonium nitrate	3.83	0.63
Calcium ammonium nitrate	1.50	0.67
Other N and compounds	1.56	0.65
Urea	10.88	0.40
Urea ammonium nitrate	5.78	0.40
Cattle slurry	12.8	0.75
Cattle farmyard manure	6.48	0.33
Digestate from cattle slurry	18.03	0.75
Digestate from cattle farmyard manure	11.80	0.75
Digestate from food and crop materials	20.23	1.00

Further evidence would be needed to ascertain and quantify these effects and compare them with the effects of reduced NH_3 deposition on catchments. Data could be extracted relatively quickly from samples collected through existing experimental platforms, to assess whether this is indeed a concern which could affect determination of the optimal approach to reducing NH_3 emissions. From a soils perspective, urease inhibitors may change biological community composition or abundance resulting in changed nutrient cycling, emissions, or availability, although there is currently no published evidence of whether such changes would be considered as adverse.

Would improved nutrient management be effective in mitigating a shift away from urea fertilisers (to reduce ammonia emissions) considering the pollution trade-offs between ammonia and nitrous oxide?

Studies indicate that there is scope for reduction of fertiliser inputs without significant loss of yield, through improved nutrient management (Sylvester-Bradley and Kindred, 2021). More accurate nutrient management planning and precise fertiliser application to meet crop needs may help mitigate the risk of additional N_2O from AN use on grassland for example, and GHG emissions from AN production. However, the scope for reduction in overall N application is difficult to quantify precisely because of lack of evidence concerning current practices. One of the core principles identified by the recently adopted UNECE Guidance Document on Integrated Sustainable Nitrogen Management (UNECE, 2021, principle 6) is that measures which reduce N losses need to be matched by reduced inputs (or by increased production) in order to realise the full benefit of the nutrient saving. Without such adjustment, measures risk “pollution swapping” and miss the opportunity for financial benefits.

Improved nutrient management is difficult to monitor and enforce, so considering how to increase farm business motivation for this could be important. Possible policy avenues are worth exploring in more detail to simultaneously support productivity and environmental goals through improving nutrient use efficiency. The farming community could contribute significantly through co-production of a strategic approach or road map to effective nutrient management, embracing all farm types.

While some reduction of N inputs could be achieved without any adverse effect on food production, some ecosystems, such as peatland, forest ecosystems and freshwater habitats, require more significant reductions in nutrient pollution transported to these sites through the atmosphere and watercourses in order to restore biodiversity. In some sensitive areas, limits may have to be placed on the nutrient intensity of particular farming systems derived from the critical nutrient load that a nearby habitat or ecosystem can bear, recognising that long range atmospheric transport of nitrogen air pollution can also have significant adverse effects.

From a climate mitigation perspective, reductions in N use in agriculture and resultant N deposition to semi-natural ecosystems may reduce additional carbon capture due to Nr fertilisation stimulation and trigger GHG emissions from these systems as the ‘fertilisation’ effect is removed (Tipping et al., 2017). Nevertheless, the full position is complex because of the contribution of N_2O to GHG emissions, while high levels (or moderate levels in some habitats) of N deposition and NH_3 concentrations lead to degradation of forests and peatlands that compromises their carbon storage. This means that identifying an acceptable input of atmospheric N differs according to the habitat type and balance of relevant impacts. As with sulphur deposition, the answer may be to more carefully target addition of N, and minimise NH_3 and NO_x emissions to avoid unintended adverse consequences for natural habitats, N_2O emission and carbon sequestration (Butterbach-Bahl et al., 2011).

What more could England do to achieve objectives set out in the Clean Air Strategy?

To reduce NH_3 emissions from 2005 levels by 16% by 2030

NH_3 reduction can be furthered through improved management of organic materials and fertilisers. England could be more ambitious with land-application measures, such as requiring the use of shallow injection and band spreading equipment for liquid organic materials on all farms (for all high N liquids, not just slurries).

Enhanced slurry store infrastructure and retrofitting or modification of existing stores should be achieved by 2030. The Clean Air Strategy has committed to make it a requirement for slurry and digestate stores to be covered by 2027, and the air quality team is working to define specific requirements for both new and existing stores.

Available research on slurry acidification shows that this is a reliable technique for reducing NH_3 emissions (UNECE Category 1 measure). Evidence from Defra Project SCF0215 suggests that reductions in ammonia emissions from slurry acidification can increase crop available N supply from slurry and digestate (ADAS in press).

To reduce N deposition on sensitive habitats by 17% by 2030 and reduce exposure to PM2.5

N deposition can be transnational, but there are also clear local effects. There is emerging evidence on spatial targeting from the Nitrogen Futures project (Dragosits et al., 2020). The current planning system may not adequately prevent the building of new potential point-sources of pollution (such as farming infrastructure that does not require planning consent) near sensitive sites, for example, Sites of Special Scientific Interest (SSSIs). Additional simple planning rules could be formulated, such as tighter restrictions applying within a certain radius of sensitive habitats. One concern is that while the retained law surrounding the Habitats Directive and corresponding regulations offers a high level of protection for Special Areas of Conservation in principle, this is not always achieved in practice. In particular, many potentially high-risk agricultural actions are not currently assessed as ‘plans or projects’ for which planning permission or environmental assessment is required. More careful redefinition of these terms and/or revised requirements for accompanying environmental information for all planning applications near to designated sites could enable the conditions of planning consent to be more carefully tailored to address such situations. For PM2.5, local measures have little effect because of the residence time of PM2.5 in the atmosphere, so national measures are needed.

What approach should government take to spatial targeting of interventions to reduce NH_3 emissions from fertilisers?

The Air Pollution Information System (APIS) has information on sensitive site critical loads. The definition and boundaries of sensitive habitats are crucial for any future policy approaches to tackle mobile pollutants. For ecosystems where air pollution and water pollution are closely linked, spatial targeting needs to take account of the permeability of the landscape, which can influence the radius affecting a given area, not just the air radius above the ground surface.

The effects of climate change and interactions with air quality will also be important over the coming years (The Royal Society, 2021). Pan-European studies have shown an increase in the flux of all materials from land to water due to recent climate change, such as P loss to water (Ockenden et al., 2017). This is partly due to stimulation of the microbial loop and also due to more frequent storms of high hydrological energy resulting in infiltration excess and overland flow and erosion. Wet winters and dry summers lead to changes in nitrate leaching curves. Food production will need to adapt: with more need for water abstraction, meaning less dilution of nutrients in surface water sources, there will be impacts on the whole system which are not yet comprehensively modelled.

Mitigation actions designed to keep carbon in the soil prioritise peatland and bogs – deep carbon stores, most of which are protected as Special Areas of Conservation for biodiversity. However, peat is especially vulnerable to N deposition, but the same amount of N going on forests, rough grasslands or heathlands may enhance their growth and sequester more carbon in plant biomass and soils (Tipping et al., 2017, 2019). Trees help scavenge N pollution from the atmosphere, however it is important to recognise that trees and plants can also be damaged by N pollution, reducing C sequestration. This suggests an approach which uses carefully targeted types of forestry or agroforestry as a buffering mechanism to intercept nutrients and sequester carbon simultaneously (Bealey et al., 2016).

Wider nutrient management policy considerations

Different policy options can be strategically sequenced within timeframes that help incentivise the sector's move from a first option to be implemented initially, to a second option that may require more time to achieve, such as a technology development or other more ambitious adaption. Outcomes should be closely monitored and linked to review points.

A coherent long-term vision and strategy would help to get stakeholder buy-in and cooperation and increase the cost-effectiveness of policy. Bringing in separate, quite significant changes without a clear sense of overall direction risks undermining stakeholder confidence and producing perverse or unintended side-effects (like shifting the problem from air to water or vice versa). There is a Clean Air Strategy in which the measures to reduce ammonia should fit, but not yet a clear nutrient management strategy that deals with the wider challenges including other pollutants. The policy trajectories taken in other countries, such as Denmark, offer useful examples to build on. Involving practitioners in co-developing the key elements of such a strategy offers potential knock-on benefits for compliance and long-term sector performance.

Good nutrient management planning is central to achieving better outcomes – both environmentally and for productivity. Research suggests that farm-level plans, where they exist, are not always strictly adhered to or used to best effect. More effort is needed to support widespread and effective nutrient management planning with an appropriate package of policy tools including standards, advice and incentives.

The RB209 guide, the most comprehensive set of nutrient recommendations produced from decades of trials, is based on pursuit of the economic optimum. Its recommendations are not limits, but provide guidance on the level of nutrients required to provide the best financial return for the farm business and minimise losses. Consequently, it may not be appropriate to use RB209 as a basis for environmental regulation and standards. Nutrient management planning also heavily relies on estimated values rather than systematic organic material and soil testing. This is a problem where organic materials and soils have wide ranging variability in their nutrient content. More regular and widespread testing of both soils and manures should be encouraged or required as well as post-harvest grain analysis to determine how effective nutrient management strategies have been.

Independent and impartial farm advice is likely to be central to achieving effective and widespread adoption of higher standards to meet environmental targets.

There is scope for Nitrogen Use Efficiency (NUE) to be improved, including through the 4R approach (right form, right time, right rate and right place, especially for organic manures), as well as optimising soil pH and P, K and S availability to ensure they are not limiting N uptake by crops.

The diversity and distribution of farming systems across the country, and their specific economic constraints, present different challenges. Excess manure generation and application in some livestock-based systems leads to excessive nutrient loading, while arable systems in the east of the country rely heavily on inorganic fertilisers.

Inorganic fertilisers have until recently been relatively cheap, so the economic incentive to use them more sparingly has not been strong. However, bought-in fertilisers are a major cost to many UK farms and the opportunity to reduce costs can provide a driver for better nutrient management.

The relative prices of different types of fertiliser impacts farm-level choices. The rapid and significant increase in inorganic fertiliser prices since 2020, linked to the international energy crisis, provides impetus to accelerate actions to reduce the proportion of nitrogen that is wasted.

Ambitious targets for NH_3, such as the government's NH_3 reduction targets, may need to be approached not just through specific practices (fertiliser type or application, manure storage and application methods), but also through wider farming systems, land use and food consumption change.

Concluding remarks

Reducing N sources is critical for tackling air pollution.

1. Understanding the timing and sequence of government intentions to commit to targets and measures for agriculture is essential so that the farming industry has a clear view of how policy will change and is able to prepare for that, in the short, medium and longer term.
2. Defra must take a holistic approach to air alongside other environmental targets. Some air quality indicators such as NH_3 emissions are relevant at a local scale while formation of PM2.5 is relevant at a national scale and needs national measures (some of which will come from measures to control NH_3).
3. More public and private investment is needed to support farmers to transition to more sustainable land management through investment in infrastructure and equipment and/or system change.
4. Increasing N use efficiency and achieving N balance on farms, while also reducing total nutrient loads, will be essential. The 3 to 4 fold increase in fertiliser prices since 2020 will motivate stronger action to cut waste in nutrient use.
5. Strengthening the availability and consistency of on-farm advice and guidance through public and private collaboration would help individual farms tackle individual problems more effectively.

Water quality

Defra briefing

In the UK, more than 50% of nitrate, 25% of phosphate and 75% of sediment loadings to the water environment are estimated to come from farming (Environmental Land Management (ELM), 2021), while other studies have suggested 75% of N and up to 50% of P are derived from agriculture in UK freshwaters, nationally (Greene et al., 2015). Others, focusing on nitrate rather than total N flux suggest that agricultural activities across England (and Wales), account for 50% to 60% of nitrate losses to the water environment, 75% of sediment, 75% of pesticides and 20% to 30% of P (National Statistics, 2021a). At catchment scale, and in particular in rural catchments, the percent contribution of agriculture to nutrient pollution is much higher as population density and sewage discharges are proportionally lower here than downstream from major urban centres.

Defra continues to manage retained /assimilated law with reference to legislation around nitrates. Following the most recent Defra review of the designation of nitrate vulnerable zones published in late 2020, these designations have been maintained as the scale of N pollution remains largely unchanged. Defra continues to work with farmers to implement the Farming Rules for Water, publishing statutory guidance on the rules with the intention of providing clarity on the key steps that farmers should follow to minimise pollution risks (Defra, 2018c). Enforcement capacity has been increased, with Defra hiring a further 50 inspectors with the aim of conducting around 4,000 inspections of farms per year.

Defra has expanded the Catchment Sensitive Farming programme to cover the whole of England. This programme of advice and information has proved successful in increasing the uptake of regulatory and voluntary actions to address water and air pollution as well as increasing the uptake of agri-environment schemes.

Agri-environment schemes and other payments will be a crucial part of Defra’s approach to N and other forms of pollution, through Countryside Stewardship and new Environmental Land Management schemes that will all contribute towards tackling pollution problems. The Sustainable Farming Incentive (SFI) aims to incentivise actions that enable better environmental outcomes whilst maintaining production. Defra has already piloted and rolled out some aspects of this scheme, including on soil management, and is exploring further aspects including nutrient management, grassland management and waterbody buffering. The Local Nature Recovery scheme will look to go beyond this and incentivise the take up of actions that require more specific land management changes and habitat creation, including looking at how to target these to deliver greatest value. Finally, a Landscape Recovery Scheme will look to deliver environmental outcomes at scale, encouraging farmers and land managers to work across multiple holdings to deliver local priorities. The Farm Investment Fund supports farmers to improve farm infrastructure and equipment through capital grants. One strand of this is focused on providing grants to improve and expand slurry stores as well as providing covers, and for equipment to enable manure testing and precision applications (all up to 50% of eligible costs), in aid of improving productivity whilst minimising losses to the environment.

Defra has recently consulted on a legally binding target on reducing N, P and sediment pollution from agriculture, proposed at securing 40% reductions by 2037. Defra has also committed to producing Environmental Improvement Plans that set out how we will work towards delivering improvements to the natural environment.

Questions to NMEG

1. **What is the most effective way to regulate for safe and productive Nutrient Management?**

By 'effective' we mean comprehended and complied with by farmers without reliance on agronomists (and, or equivalent advisors), and large numbers of farm inspections/sanctions. We'd be interested in any other approaches to regulation which may have been successful in the past or elsewhere.

By 'safe' we mean nutrients are used in a way that minimises or eliminates the risk to the environment from nutrient run-off and leaching.

By 'productive Nutrient Management' we mean nutrients that have been applied to crops at the right time, in the right way and in the right amount in order to get the best crop yield whilst limiting the damage to the environment through diffuse pollution.

2. **How could this way of regulating be adapted if we needed to constrain nutrient use further to protect sites with significant conservation value that are especially sensitive to nutrient pollution?**

Nutrient use regulations may need to be stricter near sites with significant conservation value, such as Sites of Special Scientific Interest, and internationally important sites including Special Areas of Conservation, Special Protection Areas and other important wetlands (Ramsar sites).

NMEG discussion

Atmospheric deposition of nutrients to water and land

A range of authors (James et al., 2005; Durand et al., 2011; Yates et al., 2019; Poikane et al., 2019; Wymore et al., 2021) have demonstrated that the likely background state of natural waters (annual basis) is likely to be around 1.5 to 2 mg L^{-1} total N. This should be referred to as the 'reference' or 'baseline' state for UK waters. Deviation from this threshold could be used to indicate the degree of pollution in any freshwater ecosystem, in terms of the conditions experienced by species in the water body and the likely impact on ecosystem health and function. It should not be proposed as an absolute target, but as a reference point to inform discussion about what can be tolerated from agriculture and other sources of N to water. A feasible and viable target will sit in the space between current condition and this natural background concentration. The same argument is also applicable for P, with natural background concentrations in freshwaters in the UK at around 10 to 35 µg P L^{-1} (annual mean) in lakes and up to 50 µg L^{-1} of P in rivers, against which deviation from current state and targets should be set (Vollenweider and Kerekes, 1982; Moss et al., 1996; Istvánovics, 2009).

As the air quality discussion has shown, N from a variety of sources is present in the atmosphere. This N is deposited on land and on water. At Rothamsted, amounts of annual N deposition are currently at levels last experienced at the beginning of the 20th Century (Storkey et al., 2015). Goulding et al. (2000) measured and calculated amounts and concentrations of nitrate leaving agricultural land during the 1990s. Even on plots where no fertiliser N has been applied since 1843, losses were of the order of 10 mg N L^{-1}. The Environmental Change Network (Morecroft et al., 2009. Figs 3 and 5) has been monitoring and recording atmospheric, soil and water parameters at many sites throughout the UK for the last 25 years or so. Levels of N in rainfall exceed 2 mg L^{-1} in the worst cases. Total atmospheric deposition can be much greater, although as found by Storkey et al. 2015, this has declined recently.

Considerable efforts will be needed to reduce nutrient losses from agricultural soils to the levels that would be needed to achieve the reference or baseline concentration in surface waters. For example, levels of atmospheric deposition of N in low rainfall areas are such that lakes and rivers are close to the reference level without any agricultural input. Soil might be expected to process and reduce some N applied by farmers before it is removed through plant uptake, net sequestration in soil biomass and binding to soil particles, or through denitrification, although rates will vary in both space and time. Denitrification is the dominant removal process for N in many soils (Nr) but it generally removes no more than 60% of the annual Nr deposited on natural terrestrial ecosystems. Therefore, the risk of chronic N saturation in soil and subsequent loss of N into surface and groundwater becomes very likely whenever N deposition exceeds the N removal capacity by denitrification (Sgouridis and Ullah, 2015). Similar challenges exist for reduction of P enrichment of waters from agriculture, with substantial pools of P accumulated in soils and aquatic sediments which will continue to flush from land to water over decadal timescales (Brownlie et al., 2022 and Cordell et al., 2022; Masso et al., 2022; Johnes et al., 2022).

Approaches to resolving nutrient enrichment impacts in waters have set aside the challenges of achieving reductions in concentrations to very low levels, and focused instead on practical measures that farmers and others can achieve and that are expected to bring about meaningful changes in water quality (Blackstock et al., 2010, Inman et al., 2018). The environmental benefits of these approaches are yet to be demonstrated in England, but evaluations have been positive about their general influence on farming practices (Natural England, Environment Agency and Defra, 2011), and studies from other European countries show that long-term approaches using regulatory standards coupled with tailored advice and incentives can be effective in improving water quality (Kronvang et al., 2008; Dalgaard et al., 2014). Defra should set targets which are ecologically meaningful in the context of the defined natural concentrations and which, if achieved, will support the recovery of biodiversity in freshwater ecosystems, reducing nutrient (N and P) losses from agriculture to water whilst not increasing N losses to air.

What is the most effective policy approach for achieving water quality targets?

There was consensus in the Group that in this particular context, regulation will only be effective when rolled out together with a comprehensive package of supporting measures, including training, targeted advice, and support for peer-to-peer learning and knowledge exchange networks – all of which would need to be properly resourced and funded. It will also benefit from a supportive approach by the regulator, such as is discussed in Defra's Agricultural Transition Plan (Defra, 2020, page 31). The NMEG agrees that co-design of environmental management and consensus on standards between regulator, land-managers and scientists is the best means to deliver continued improvements in environmental quality, whilst retaining the ability to produce food from UK farming systems.

Effective support to enable full compliance requires well-trained, skilled advisers – whether they work for the regulator or in another publicly-funded capacity, ensuring that the advice is not unduly influenced by commercial interests. The current inspection and enforcement resource for water quality regulations is very low - t 91 Environment Agency Officers to cover around 100,000 farms across the whole of England, following cuts over the past decade. A well-funded, independent but supportive regulator is essential, in this context. Requirements for farmer training or certification of competence would support advisor and sector upskilling and engagement.

Looking beyond regulation, some learning can be effectively achieved in groups, by farm-scale demonstration of practices and 'champion farmers' disseminating good practice, but individual farm visits by an advisor will likely still be necessary to offer advice on the individual challenges faced by each business. Engaging farmers with water quality targets is particularly challenging because farmers may not clearly see the impact of their practice on groundwater and freshwater quality. Improvements in freshwater can take a long time to become evident and are not necessarily visible. Roll out of citizen science techniques to collect, identify and monitor changes in fish (through local fishing associations), macroinvertebrates (through kick sampling, and identification using standard keys), plant extent and species identification, or examples such as the recent roll out of the UKCEH 'Bloomin' Algae' app to track algal blooms in lakes, could be used to raise farmers' awareness of issues and engagement in community-led mitigation efforts.

Engagement with farmers will be more effective if scientists and policy experts better understand the practical realities of farming and develop empathy with farmers through more dialogue and on-farm collective learning opportunities. The development of 'communities of practice' spanning the academic, farmer, farm advisor, regulator and environmental NGO spectrum has been shown to help foster vital trust (Mills et al., 2011; Sutherland et al., 2013).

Such partnership working is important in order to achieve consensus on objectives. Regulations need to be developed jointly with stakeholders, and their interpretation needs to be agreed between key actors including farming organisations, prior to roll-out. The development of Farming Rules for Water (FRfW), for example, was initially reported by farmers' organisations to be a positive approach because it attempted to cover a range of issues together. However, the EA's interpretation of the rules has not conformed to prior expectations and proved unworkable for many (Chivers et al., in press). Much more thorough prior discussion with those affected and the use of clear, unambiguous language are required to prevent differences in interpretation and increase effective responses.

NMEG welcomes the news that Catchment Sensitive Farming, where dedicated advisers work with farmers in specific catchments, will be rolled out across the whole country and tackle all nutrient-related pollution of water. Tightly targeted implementation had previously wrongly implied to farmers outside target areas that their water quality and nutrient losses were not a concern. As sites differ so much in terms of their ecology and specific agricultural pressures, localised action plans are considered essential.

Individual farm nutrient budgets (calculating the ratio of nutrient inputs to outputs), with target levels agreed for the local area, may be an approach that could build in nationwide principles delivered with local specificity. However, nutrient budgeting is complicated and requires interpretation for a range of measures and outputs, so would likely require support from farm advisers. Nutrient budgeting can be very valuable as an educational tool to raise farmer awareness. It can also be used at a regional scale to estimate the approximate surplus or deficit within a given area and identify specific nutrient management 'hotspots' or issues where additional targeted support by the regulator is required.

Good nutrient management could include a requirement for farmers to justify all their nutrient use based on their own achievable yields, following the approach recommended in RB209, tailored to the intensity of each production system.

A better understanding of the drivers behind current non-compliance is required, to inform the design of realistic and achievable measures.

How can we best manage manure and slurry to protect water quality?

Businesses such as livestock units with insufficient access to land on which to effectively and safely use the nutrient sources they generate could be treated in a way similar to pig and poultry operations under the IPPC Regulations. Environmental permitting is appropriately being extended to beef and dairy units of a similar scale and intensity of nutrient management operations. These require certification and inspections and impose a requirement to justify how excess nutrients will be safely managed (as applies to N, in Nitrate Vulnerable Zones or NVZs). However, smaller livestock farms can also be hotspots for excess nutrient loading (Lloyd et al., 2019); which requires a simpler but equally effective approach to reduce applications. In some local areas, farmers with low nutrient loads can be advised or encouraged to use the excess nutrients from other farms with surpluses of manure and slurry.

The draft Post-Implementation Review of the nitrates and Silage, Slurry and Agricultural Fuel Oil (SSAFO) regulations indicates a need for greater clarity around autumn crops' requirements for N. The closed period dates in legislation allow for manures and slurries to be spread before the start of the closed period. Fixed dates may be easier to prescribe and police but can also have unintended consequences in leading to more concentrated spreading just before and after the closed period dates, with potential peaks in ammonia pollution for example. Insufficient slurry storage capacity is one of the drivers behind increased spreading just before closed periods, so investment support as in the Farm Investment Fund can be helpful – however, this will not solve issues of excess loading, on its own and an assessment system is needed to guard against locking farm businesses into systems which ultimately cannot be sustainably managed, economically and environmentally. Manure management guidance should deal with the balance of pollution risks rather than focusing on only one pollutant pathway or contaminant form. It should also account for other factors such as soil type, cropping system and practical constraints.

A more strategic and joined-up approach to delivery is needed to support simultaneous improvements to air and water quality, such as through covered slurry stores or use of slurry bags. The Defra Air Quality team is working to define appropriate new requirements for slurry stores and covers, and funding options. Greater consideration should be given to encouraging systems built around more sustainable stocking, calculated as part of a farm-scale nutrient budget.

The cost to farmers of new infrastructure is a significant barrier to effective regulation (particularly due to the pre-1991 exemption in current rules). If improved infrastructure provides a mainly public rather than private benefit, there is a case for such investment to be funded at higher than the normal 40% or 50% rates by government, or for loans for such investment to be underwritten by public bodies rather than farmers themselves. Considering the balance of public and private benefits flowing from such infrastructure and its main beneficiaries (such as water companies' consumers), could inform policy decision-making as regards the most appropriate balance and sources of funding to enable its provision.

What other policy approaches could be considered to protect water?

Evidence from other countries (for example, Denmark and the Netherlands) shows positive results linked to comprehensive, multi-instrument policies with standards that have been gradually tightened over 30 to 40 years, to change practice and strengthen rules. This suggests that there may be no quick fixes for effective and environmentally safe nutrient management, but rather longer-term, cumulative strategies that need to co-evolve in collaboration with the sector.

A useful approach would be a flexible policy package that includes nutrient management planning as a central practice on all farms, enables calculation of nutrient fluxes, encourages good recording, and fosters farmer learning, at farm level (through a tool such as MINAS or Overseer). This approach could also include using specific policy mixes that can be varied over time, with tools (advice, requirements, incentives) adapted to the context and needs of specific locations.

The use of mitigation methods such as catch or cover crops, to absorb excess N and prevent leaching should be encouraged, along with a range of other practices and techniques to lower input use without compromising farms' financial performance.

There may be a role for private sector corporate contributions to fund instruments and advisory support. Water companies and other private sector companies have an interest in investing in co-benefits, through initiatives such as the Landscape Enterprise Networks ((LENs), 2022). Water industry nutrient trading schemes such as 'Entrade' may help mitigate nutrient pollution, but evidence of their effectiveness, cost and inclusion should be shared with policy makers and be peer-reviewed (Entrade, 2022). Water company investment is at present designed to reduce the costs of 'end of pipe' treatment, but it has potential to incorporate other public benefits at the same time.

How can we best protect sites with significant conservation value that are especially sensitive to nutrient pollution?

Nutrient use regulations may need to be stricter near sites with significant conservation value, such as Sites of special scientific interest (SSSI), Special Areas of Conservation (SAC), Special Protection Areas (SPA) and others. The legislation giving special protection to such sites has not stopped them declining due to nutrient pollution. This could be due to insufficient incorporation of nutrient-limiting conditions in protection mechanisms (such as Operations Requiring Natural England's Consent included in the formal SSSI notification process), or to poor enforcement, or to insufficiently ambitious targets (not reflecting the natural conditions to which species and ecosystems are adapted) being included in the regulations. Many surface water SAC designation boundaries are inappropriate to tackle nutrient issues because they capture only the river distribution or habitat itself, and fail to include the catchment that feeds it.

Nevertheless, adopting a specific approach only to designated conservation sites implies that not all areas are sensitive to nutrient loadings, which is incorrect. A consistent, principled approach to nutrient management on all land may therefore more appropriately recognise that excessive nutrient loading is damaging, wherever it occurs.

One benefit of a nationwide approach is that it treats all farmers equally. In recent years, farmers in NVZs and other designated areas have felt discriminated against, which has impacted on trust and engagement with the regulations and their goals. At the same time, farmers and scientists question the efficiency of rigid national measures to achieve outcomes, so an adaptive approach with locally-set and reviewed standards could be perceived as more appropriate and generate higher engagement.

There is a case for new regulations to apply to all waters: a simple set of rules for all farmers would be more likely to be complied with, provided farmers are given supporting advice, training and other low-cost and accessible opportunities for learning.

An effective policy approach could be similar to that of spatial planning policy, which has a set of high-level national principles and detailed policy guidelines about how things should be done, but individual decisions - on what to permit and under what conditions - are devolved to local level to reflect differences in local context. The local governance of such a system should ideally involve partnership between regulators, local stakeholders and scientists and research experts.

Concluding remarks

The water environment is particularly sensitive to both point source and diffuse pollution from N and P. Different landscapes under different farming systems will react differently to N and P contamination and impacts on aquatic ecosystems will vary according to the particular environmental conditions at each site. Future policy frameworks should ensure that measures can be applied from farm level to catchment and national level. They should be adaptable in response to the evidence base which must include continued monitoring of water quality (both physio-chemical and biological). Partnership or community approaches building evidence, at the same time as building trust between farmers, advisers, researchers and policy makers at a local or regional scale are critical for successful implementation of policies.

Key Points:

1. Dealing with atmospheric sources of N is challenging and targets need to recognise that ecologically acceptable levels are different to those common in modern agricultural landscapes. Returning sensitive sites to much lower levels of N may require very stringent reductions (including outright bans) of nutrient inputs, in some locations.
2. Nutrient budgeting could be an effective way to regulate overall nutrient loading at farm, catchment, regional and national scales. It can however be complicated so should be supported by technically skilled and experienced advisers if it is to be effective.
3. Robust and more comprehensive support and funding for partnership working, enabling upskilling and knowledge exchange between farmers, advisers and

farmers, and scientific researchers, policy makers and farmers, would significantly enhance the achievement of targets linked to regulatory measures.

4. Appropriate farm infrastructure is essential for reducing pollution incidents from manure management, but should be designed to avoid locking farms into systems that are not ultimately economically or environmentally sustainable. With that proviso, grants or loans can usefully help farmers provide adequate manure storage capacity and more generous rates of grant (for example, above 40% of costs) rates can be justified on the basis of the public benefit that this provides. Bringing manures and slurries into nutrient budgeting at farm scale, and balancing stocking densities with environmental carrying capacity may also reduce the need for additional storage facilities.
5. All waters are sensitive to nutrient enrichment, therefore national policy frameworks are necessary to protect all waters.

Soil health

Defra briefing

Healthy, functioning soil is the foundation of our natural resources, underpinning a range of essential ecosystem services and outcomes including food, fibre and timber production, biodiversity, carbon storage, flood and drought mitigation and improved water quality (Figure 1). They are multifunctional, complex ecosystems that need to be managed appropriately to deliver this range of key ecosystem services. Nutrients are at the heart of many of these functions, and so soils are an important component to be integrated into nutrient management and policy.

Figure 1: Schematic diagram of soil functions. (Source: [FAO](#))

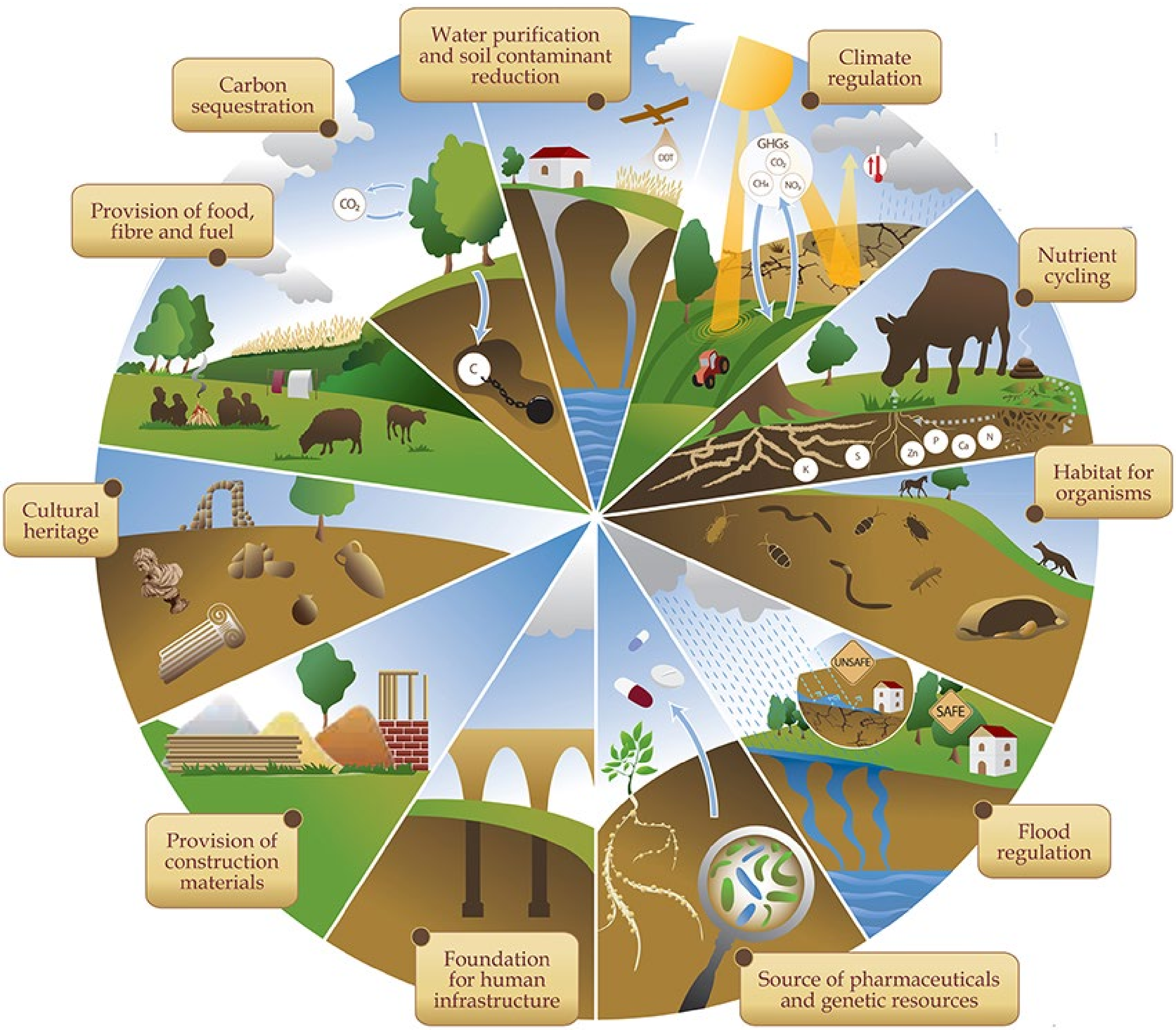

Figure 1 description: a circular diagram with 11 segments. Each segment includes an image that represents each of the different soil functions.

Specific functions of soil include:

- water purification and soil contaminant reduction
- climate regulation
- nutrient cycling
- habitat for organisms
- flood regulation
- source of pharmaceuticals and genetic resources
- foundation for human infrastructure
- provision of construction materials
- cultural heritage
- provision of food, fibre and fuel
- carbon sequestration

Soil's ability to deliver these functions is reduced when it is degraded, eroded, compacted, contaminated or has lost its structural components completely. Soil degradation in England and Wales has been estimated to cost up to £1.84 billion a year (Graves et al., 2015). This cost is mostly due to loss of organic matter content (47%), compaction (39%) and erosion (12%).

Improving soil management practices in England is essential to reduce the environmental, economic and societal impacts of soil degradation and meet Government's commitment to have sustainably managed soils by 2030, as set out in the 25 Year Environment Plan. The target states: 'by 2030 we want all of England's soils to be managed sustainably', as well as improving soil health which starts with the development of a soil health metric. Improving soil management practices in England also supports the wider ambitions of Net Zero, Green Recovery plan, the Growth plan and the Biodiversity Strategy, as well as contributing to the ambitions of the Environmental Land Management Scheme to drive environmental benefit and support our rural economy through effective incentivisation.

Policy is developing rapidly in relation to soil health. This includes the Soil Health Action Plan for England, that will be crucial in driving progress across government to restore the health of our soil. It will include developing a suite of healthy soil indicators, soil structure methodology and soil surveys under the Natural Capital Ecosystem Assessment, a new evidence programme to assess the condition of the environment which will also include soil monitoring. The Sustainable Farming Incentive scheme also provides incentives for farmers to do certain actions in relation to arable, horticultural and grassland soils.

The term 'soil health' has many definitions, but largely it refers to the capacity for soil to function as a living ecosystem and provide ecosystem services[4] such as food, biodiversity,

[4] For more information on the principles of ecosystem services see https://www.millenniumassessment.org/en/index.html

carbon storage and mitigation of flooding and drought. Whilst soil health as a concept has been criticised for having little meaning without reference to a specific use or expected function (Baveye, 2021), the benefit of the term is that it is effective for communicating with non-specialists who have capacity to influence management of soils.

Soils are a complex ecosystem made up from a mix of organic matter, living organisms, minerals, gas and water. Most of the organic matter in soils is made up from residues of living things – plants, animals and micro-organisms – in varying states of decay. These residues contain nutrients, as all living things are made up of these basic building blocks. The organic matter also includes, however, living organisms such as bacteria, fungi, plant roots, and protozoa which form very diverse communities. Soil microorganisms break down organic compounds in the soil, releasing energy, carbon and the nutrients that they need to live. Nutrient management practices used on farms can impact, both positively and negatively, the health of agricultural soils.

Questions to NMEG

1. Which nutrient management approaches (input types, application methods and others) best support overall soil health, and its individual aspects (such as soil structure, soil organic carbon, biological diversity, pH, nutrient storage), as well as productivity and the wider environment?
2. Which soil management techniques (such as minimum tillage and liming of soil) can best support effective and efficient nutrient management, as well as the wider environment?
3. What should a new Soil Health Action Plan for England (SHAPE) include, to successfully discourage poor soil nutrient management practice, increase knowledge, and encourage effective nutrient and soil management planning (for example, through collaborative networks, formalising knowledge sharing, or through amending or introducing new regulations)?

NMEG discussion

Should farmers favour organic or inorganic inputs to soils?

Broadly, excess nutrient applications, whether organic or inorganic, should be avoided. Excess application of organic materials can lead to significant N, P and C pollution of soils, aquifers, surface waters and the atmosphere through GHGs, ammonia, and odour. The crop available nutrient supply from organic materials is typically more variable than that from manufactured fertilisers, as they derive from variable natural sources rather than a specific manufacturing process with controlled inputs. Hence, nutrients supplied from inorganic fertilisers and from organic materials such as manures, digestates, compost and biosolids all need to be included in nutrient management plans and accounted for.

The advantage of organic inputs is that they return organic matter to the soil. Soil organic matter is important for many soil functions, including supporting biological activity, water and cation exchange capacity, and carbon storage. There are also indications from field experiments (Whitmore et al., 2017, Bhogal et al., 2018) that different types of organic material influence soil properties in contrasting ways. For example, repeated applications of compost have been seen to increase soil organic matter levels more quickly than applications of farmyard manure. In contrast, higher levels of soil microbial biomass have been measured where manure has been applied, compared to compost.

There are significant evidence gaps in research on the uptake by crops of nutrients in organic form, so policies that enable this learning, and can deal with current uncertainties, are necessary. Understanding the capacity of soils to store organic matter is important, as a single target value for organic matter content will not be appropriate for the range of soil types, land uses and climatic zones across the UK. More research, for example from experimental farms, would be helpful and could be supported and disseminated by knowledge-sharing networks.

How do anaerobic digestate and compost impact soils?

Anaerobic digestion (AD) involves the decomposition of biodegradable feedstock under low oxygen conditions. In addition to the biogas and heat generated, this process results in the generation of digestate, which can be separated into several products (both liquid and solid) with different nutrient contents that can help to reduce reliance on manufactured inorganic N and P fertilisers. AD has the potential to transform organic waste into useful fertilising products, which we discuss in more detail in the Circular Economy chapter of this report. However, its impact on soil health must be fully considered.

The anaerobic digestion of organic materials could improve the predictability of their nutrient availability, though the composition of digestate from different AD plants will vary according to the feedstocks used in the AD process. Food-based digestate generally contains a high proportion of ammonium-N and application rates should be managed carefully to reduce the risk of excess N application. The use of band spreaders to apply digestate will reduce the risk of ammonia loss and spring application timings will reduce the likelihood of nitrate leaching losses following application.

Composts are stabilised forms of organic material with crop available nutrient supply, although less N than AD typically. While composts are more stable there is still a risk that NH_3 and N_2O can be lost from the material during the composting process (Pardo et al., 2014). Some predictability of, or consistency in, nutrient content and availability is critical for applying the recommended amounts of nutrient to crops and avoiding pollution from excess N or P. Of course, organic materials are not readily available on all farms or in all parts of the country but using them more efficiently could help improve soil health.

Composts and digestate tend (although not always) to be produced from what would otherwise be considered as waste if made on large scales. To achieve end-of-waste criteria certain standards must be met, these are the Quality Protocols (QP) and the PAS 100 (composts) and PAS 110 (digestate). These standards assess the production process and that the end product is safe to apply to land and ensures their nutrient content is established. Manures and slurries are not automatically subject to these standards. However, compost and digestate may introduce chemicals and physical contaminants, including microplastics, into soils. While many risks are dealt with by these standards there continues to be a need for improvement as potential hazards become apparent. The Environment Agency is currently reviewing the QPs especially regarding the plastic limits that are currently set.

When should organic materials be applied?

The risks of environmental pollution vary according to manure type and also depend on application method, timing, soil type and weather conditions after application. So, we cannot have a ‘one-size-fits-all’ approach to their use.

Flexibility in the timing of application of organic materials is important, to enable farmers to manage their stocks of manure, and the condition of the soil at the time of application is the key factor in minimising pollution risks to air and water.

Currently, the classification of organic materials has a demarcation between high-and low readily available N contents. Materials with less-readily-available N such as farmyard manures, composts and biosolids (all of these caveated, depending on their input materials and storage conditions), are generally more appropriate to use in the autumn when they can be rapidly incorporated into the soil to reduce NH_3 emissions. On free-draining soils where water moves to depth in one phase, nitrate leaching is likely to pose the greatest risk of diffuse pollution following manure applications (Chambers et al 2000 and Bhogal et al., 2021). In contrast Defra project WQ0118 showed that on clay soils where rainfall results in water moving rapidly from the soil surface to drains, spring applications posed the greatest risk of P loss and soil compaction, due to increased risk of applications being made to saturated soils (this is in accord with the recent review of interpretation of rule 1 of the Farming Rules for Water, and the environmental impacts of shifting organic material applications to the spring) (Bhogal et al., 2021).

While the factors controlling nitrate leaching, NH_3 volatilisation and nitrous oxide emissions from organic material applications are understood, there is much less understanding of the risk of P from manure applications on water quality, and specifically with regard to P availability in different types of manure, the impacts of repeated applications on soil P, and leaching losses.

Regular and quick analysis of organic materials and the use of regularly updated tools such as 'MANNER-NPK' to assess their nutrient availability, should help improve nutrient use efficiency. However, there are practical challenges to taking representative manure samples (despite available guidance) and the costs of sampling and analysing manures (or other organic materials) may present barriers to uptake. Grant schemes and, or obligations to do regular testing, for example through regulations or via produce assurance schemes, may be effective at demonstrating the value of the nutrients supplied by organic materials. The recent significant rise in the cost of chemical fertilisers may also encourage farmers to give more attention to nutrients from organic sources.

Sustainable soil management

No-tillage or minimum tillage soil tends to have higher concentrations of organic matter in the surface soil, whilst ploughing turns the soil and dilutes the same amount of organic matter in the ploughed layer. Organic matter retained in the upper layer (as with no-till) helps the soil resist erosion better, and water infiltration can be improved. Tillage breaks up aggregates, reducing soil stability while aerating the soil and increasing organic matter decomposition, release of CO_2 and the risk of erosion, but it has value for weed control whereas in no-till systems this may require herbicide use. No-till cannot be used everywhere, and the benefits and trade-offs will vary depending on several factors including soil type, crop type, season and weed pressures among others. A global meta-analysis concluded that: "both absolute and relative yield stability did not differ between no-tilled and conventionally tilled fields for the overall dataset and for crop species with at least 10 observations" (Knapp and van der Heijden, 2018).

Tillage can negatively affect soil nutrient availability through its role in redistribution of soils. Loss of soils upslope leads to thinning profiles with decreased soil organic matter, and there is a risk that nutrient poor subsoils get mixed into the top layers and deposited downslope, decreasing soil organic matter in the plant-accessible layers (Quinton et al., 2022).

Maintaining year-round soil cover is valuable for soil stability: this can be achieved using cover crops or under-sowing techniques. Stable root systems help support soil health, so perennial crops, permaculture and agroforestry will also offer these benefits. Short-term farm business tenancies, licences or land management contracts can hinder longer term rotations by disincentivising land managers from investing in long-term rewards. Farmers also need to see a market for what they are producing: policies which support long-term contracts or under-write investment actions may therefore be useful. Planting trees as buffer strips, interrupting flow pathways linking soil to water, can be very effective in improving soil retention, reducing water flow, sediment and particulate-bound nutrients reaching waters. Tree planting initiatives in appropriate locations could yield multiple benefits for soil biodiversity, carbon sequestration in soils, and reduced nutrient and sediment pollution.

Grassland soils will almost always have a higher organic matter content than arable on the same soil type because of continued, year-round input from roots and residues, inputs from manures and excreta if grazed, and because their structure is not disturbed. Mixed farming systems – where land use is rotated between grazing and cropping - may be advantageous from a soil health perspective.

Compaction of soils used for agriculture, horticulture (and forestry) can be caused by machinery or livestock crushing the soil and this can occur at any time of year; however, the risk of compaction increases when soil moisture content reaches or exceeds field capacity. Mechanical loosening can temporarily improve soil aeration and water infiltration; however, to improve soil structure requires natural alleviation (facilitated by plant roots and application of organic resources) which can take many years, depending on the severity of compaction and soil type. In the absence of further compaction pressures, natural alleviation allows the soil structure to recover and become more resilient to further compaction.

The elevated organic matter present in grassland systems helps reduce the risk of compaction, but cannot entirely buffer against poor practice. Grassland compaction can still be very significant: wet soils, heavy machines and livestock at high densities cause serious compaction on low and high organic matter soils. Run-off will be greater on compacted soils. Flooding in some areas, though, has revealed that legacy compaction can exist at a greater depth than 0 to 35cm, thereby reducing water storage capacity even when the surface is not compacted, and impacting on nutrient and sediment loss.

Serious compaction is usually less of a field-scale issue than a localised one, with puddling and ponding around ‘camping areas’ (frequently used, high animal occupancy areas), feeders and farm gates in particular. This leads to run-off onto roads, from which sediments and nutrients quickly reach water courses. So, management practices within the field are crucial. Poaching of soil along watercourses, where livestock are permitted direct access, can produce locally significant sources of nutrient, sediment and potential pathogen pollution to waters. Fencing to control such access and providing alternative drinking water troughs can be very effective in mitigating these sources.

Straw is another carbon input that gives energy to microbes. It has a lower nutrient content than other materials and needs N from the soil in order to complete its incorporation into SOM, so it may also compete for nutrients with growing plants. Crop residues are useful from the perspective of returning organic matter to soil, but it is important to recognise that they also represent a significant contribution to total direct N_2O emissions from UK agricultural soils and can contribute to carbon emission if residues are ploughed in. In the current GHG inventory (Brown et al., 2019), crop residues represent the second largest source of direct soil emissions from soil (behind manufactured N fertiliser) and are almost twice as large as those from animal manure applied to soil, not accounting for N_2O emissions associated with manure management[1]. Research carried out in the Defra MIN-

NO project and the FACCE ERA-GAS ResidueGas project has shown that N_2O emissions from residues vary. ‘Green’ residues such as those from cover crops are associated with much larger N_2O emissions than ‘brown’ residues such as cereal straw. Even the toughest organic materials added to soil will decompose eventually. Adding materials with lower C:N ratios result in greater C storage as more of the added C is retained in the microbial biomass, which is more likely to enter long-term C storage. As such both types of organic matter will result in environmental and agricultural benefits, but C:N ratios of around 24 may deliver the widest range of benefits. Soil microorganisms have a C:N ratio near 8:1. They must acquire enough carbon and N from the environment in which they live to maintain that ratio. Soil microorganisms burn carbon as a source of energy, so not all of the carbon a soil microorganism assimilates remains in its body; a certain amount is lost as CO_2 during respiration. To acquire the C and N a soil microorganism needs to stay alive (body maintenance + energy), it needs a diet with a C:N ratio near 24:1. The breakdown of organic matter by soil microorganisms also releases nutrients that can be acquired by plants.

Organic matter input appears to offer some buffering against soil acidification, but any source of ammonium inputs to soil results in acidification, via its conversion to nitrate by nitrifying bacteria in the soil, which can be mitigated by liming – noting that the C in lime, a natural material, is eventually emitted to the air as CO_2 (Raza et al., 2021). If lime is replaced with waste aggregate containing calcium from silicate rocks, the link to emissions is broken.

Intercropping and cover cropping with legumes, and rotations with leys containing legumes should also be considered as means of supplying N to arable and grassland systems through biological N fixation, while also improving soil health in terms of structure, aggregation, and input of organic matter among other factors. In all-arable systems there can be practical challenges in establishing 2 crops in one field or establishing a market for grass to enable such grass to be productive within an arable rotation. There are also processing challenges, with the risk of contamination of products such as wheat flour with beans unless harvesting equipment and, or product specifications can be adapted to remove or allow for this risk, respectively. Organic systems intercropping wheat and lentils have been designed to perform commercially in France, with results suggesting higher returns from combined cropping than from either crop grown separately on the same area of land, even including the additional cost of grain sorting (Viguier et al., 2018).

Introducing herbal rich leys is also a technique that can bring soil benefits (AHDB, 2022). The different root traits of these mixes (deep and shallow) help recover soil health whilst enhancing fertility and organic matter, resilience to extreme weather (for example drought), and biodiversity and livestock health can also benefit.

Content of the Soil Health Action Plan for England (SHAPE) - What general principles could shift farms in England towards sustainable practice?

While agricultural land is likely always to leak nutrients and generate some level of diffuse pollution, this can be minimised by careful nutrient management, maintenance of soil health, and management of crop cover. Increasing soil organic matter is likely to improve soil structure and function which will support better crop growth, enhanced nutrient retention, increased crop nutrient recovery and improve water infiltration, reducing risks of nutrient sediment losses to water. Thus, policies that support increased organic matter applications to enable reduced inorganic nutrient input, as part of a balanced farm nutrient budget, and that ensure best practices to minimise the risk of increased N and P and other contaminant releases from soils to air and water, can be helpful to support soil health.

High-intensity, high input systems can produce high yields and, via economies of scale, reduce the economic and environmental costs of production (per unit product) but are generally seen as less economically resilient to unanticipated shocks of climate or disease (such as mono-culture cropping or high risks embedded with high input-cost crops). Organic farming can provide environmental benefits in many circumstances but may increase variability in crop yields (Smith et al., 2019), which are generally lower than in conventional systems (Knapp and van der Heijden, 2018). Improved organic matter content in soils could play an important role in stabilising such yields in future, as we experience increasingly frequent extreme weather events (Kane et al., 2021).

Farmers will more sustainably manage their soils and input needs if they adjust the production system to target yields at what their land can realistically produce, such as its 5-year yield average, rather than aiming for the highest yield that they might only produce one year in five. Businesses may also be more resilient when they aim for slightly reduced, but more sustainable, yields. This moderating approach could bring significant nutrient management benefits, both economic and environmental, if widely adopted. However, more drastic change, shifting operations in ways that lead to significant yield reductions across the country as a whole, could mean greater agricultural land use or higher imports of products from countries with less sustainable practices, which should be avoided.

SHAPE contents - What specific policies could Defra implement?

Defra could consider setting targets for specific services from soil (services like food production as well as other ecosystem services such as carbon storage and water-holding capacity), rather than just promoting the more generic target in the 25 Year Environment Plan of ‘sustainably managed soil by 2030’. It is important, however, that target setting addresses soils in non-agricultural settings: for example, soils in semi-natural settings and urban areas also provide vital ecosystem services and can present significant threats to water quality and flood risks, where they are not well-managed.

There is scope for defining some critical soil health indicators to be sustained, from a physical, chemical, and biological perspective. AHDB’s Soil Biology and Soil Health

Partnership have developed a ‘soil health scorecard’ and Otten (2021) also outlines different indices of potential relevance for defining soil health, which could be useful in setting such targets.

Nutrient management plans (NMPs) could be incorporated further into any potential future soil regulation (in addition to the requirements in Farming Rules for Water) that may replace the cross-compliance requirements, which are planned to phase out by the end of 2024 in England (they will persist for longer in Wales, Scotland and Northern Ireland). NMPs also feature as a requirement for some of the Environmental Land Management standards, but future levels of uptake of this new scheme for England are as yet unknown and may not be so widespread as the Basic Payment Scheme.

A farm NMP could be made mandatory, as a move to demonstrate that farmers actively manage their nutrients and soil health, although a plan alone does not evidence the practices that result from it and action in parallel to increase farm business motivation for improved practices, such as emphasising the economic and agronomic benefits, would probably be needed.

The idea of a soil passport could be a useful approach for raising awareness and breadth of soils knowledge among farmers, it could also be linked to land classification and perhaps land price to provide an incentive for land managers to improve their soils longer term. Or, this could evolve into a regulatory strategy via a requirement that the soils on a farm be ‘improved’ in condition over time. Soil health data (chemical, physical and biological indicators) is thought to be rarely provided before land is taken on by a new user; a passport could helpfully establish this practice. Whichever approach, or combination of approaches is chosen, it should be implemented as a transparent strategy so land managers are aware. A soil passport system could also be adopted in urban development contexts: whilst urban land use is a relatively small percent of total land area in the UK, in 2016, 51 million tonnes of soil were excavated in construction projects, around half of which went to landfill. This is far in excess of the total soil loss estimated to occur each year from all agricultural lands in the UK (Graves et al., 2015).

SHAPE contents – the importance of knowledge, learning and advice, and funding

Policy should have a strong focus on imparting knowledge, to allow farmers and land managers to understand the implications of nutrient management and be able to optimise their nutrient usage, while minimising the environmental damage that they cause. Farmer-farmer interactions are effective in sharing knowledge, especially where there is up to date and reliable science input, and appropriate facilitation to bring people and information together (Mills et al., 2017). The co-generation of knowledge has been identified as key in creating the sense that farmers are part of a collective journey along with scientists and policy makers, and part of the solution to these environmental challenges (Ingram et al., 2018), rather than being blamed for issues, while fully cognisant of their responsibilities.

Farmers need unbiased advice based on robust evidence in order to be well-informed about the agronomic, economic and environmental impacts of their production decisions. Continuity among advisors is key, as it takes 3 to 5 years to build trusting relationships with farmers. The longstanding publicly-funded ADAS advisors that supported farms to develop and modernise in the 1970s and 1980s were often able to build such relationships. Some farmer groups have been calling for reinstatement of such an independent, non-commercial agronomic and business advice service. Currently, advice is provided by a wide variety of commercial and non-profit organisations but it can be difficult to judge their breadth of expertise and professional quality when considering whom to approach for help, and many smaller farm businesses (particularly among livestock farms) do not have a trusted and regular professional advisory service.

Environment Agency Catchment Officers have valuable local knowledge and can be good communicators of optimal nutrient and soil management practices, but there may be value in separating advisory and regulatory roles.

A range of decision support systems is available to help accurately match nutrient inputs to soil and crop needs (for example, RB209, PLANET, MANNER-NPK, computer models, soil analysis, crop sensing), and mandating evidence of use of such systems could be considered in future policy. It is important that decision support tools (DST) provided by different organisations are continually updated and give consistent advice on nutrient management using standard terms and concepts, even if their methods or reporting capabilities are slightly different (being tailored to different market niches). There is also a need to encourage firms to invest in DSTs to make sure they can operate on current tech platforms and multimedia devices.

There is a case for more work on the clusters of available measures and solutions that would form coherent packages for farmers to implement. This has been started in the UNECE N guidance document, but needs further development. Farmers, scientists, agronomists, and other key stakeholders need to work together to produce such guidelines, as part of an evolving process.

In respect of funding: many solutions suggested to improve soil management and soil health, such as new infrastructure, stocking rate reductions or manure transfer to other farms, and the introduction of more mixed farming systems, could incur significant costs to the farmer, implying higher farm gate prices, and potentially higher retail prices. In view of the public benefit from enhanced soil health, some or all of these additional costs could be supported by taxpayers, through investment and/or revenue funding schemes. Furthermore, many actions that would benefit soil health could simultaneously offer other nutrient management, biodiversity or wider environmental benefits, thus increasing the cost-effectiveness of public support.

Delivering on SHAPE – the importance of monitoring

Repeated, standardised and open monitoring is needed at the right place and at the right temporal resolution for the right suite of determinants to provide the necessary evidence to quantify nutrient fluxes and responses to improvement and, or mitigation efforts, in respect of soil management and soil health. These include for soils: pH, SOC, C:N, total P, bulk density, infiltration rates and soil cover; for soil inputs to water, determinants should include dissolved organic carbon, total N, total P and suspended sediment in water bodies. Monitoring also represents a vital source of information for learning among farmers, advisors and policy makers.

NMEG believes that any new farm support scheme should include soil sampling of nutrient and pH status and condition as a matter of course or basic requirement, so that there is a much wider understanding among farmers of what they have, and what can be done. This not only has benefits for the farmers but also for the government, as it provides a database of soil condition across the country. Farmers and policy makers need to understand better the basics of what is in our soils before we can change policies and practices to enhance conditions.

When considering soil losses to water, one of the greatest current constraints on learning is the lack of adequate and timely water quality monitoring that fits this purpose, allowing catchment managers to identify changes due to farming practice. There is currently no information on the extent of organic pollution of water. A simple holistic measure, comprising total N, total P and suspended solids, plus dissolved organic carbon, measured at high frequency, must be introduced to measure the right things (including physical, chemical and biological characteristics) in the right places, at the right frequency to capture episodic delivery events, and provide the evidence needed to underpin policy, management and reporting.

Concluding remarks

Managing healthy soils and managing nutrients often go hand in hand. The balance of N, P and C is particularly important when managing nutrients in soils and when planning the ratio of organic to inorganic nutrient inputs to soils. It is clear that little national-scale monitoring has taken place to evaluate the ongoing evolution of soil condition on farms, and especially to relate it to on-farm practices. A comprehensive testing and monitoring framework should be put in place, alongside access to appropriate decision support tools and suitably accredited technical advice to enable better planning of nutrient inputs to soils, especially with a focus on managing soil organic C. Finally, in order to better enable farms to adopt new management practices and more resilient farming systems that will protect and improve soil health, there is a clear case for public funding.

Key points:

1. Increasing soil organic matter and focusing on farming systems that enable fewer inputs to be used could help build soil health while enhancing nutrient use efficiency if managed carefully. To encourage farming system shifts towards more resilient approaches such as these, public funding both for investment and for ongoing management can be justified.

2. Longer term and regular soil monitoring should be practised on all farms and records made available to policymakers; potentially it could be implemented as part of a soil health passport policy, and it could be supported as a basic requirement of SFI. Testing should be funded appropriately to ensure widespread uptake across all land-based farm sectors.
3. The importance of impartial expert advice on farms, and connecting farmers with other farmers or researchers, is under-estimated and often underfunded.
4. Monitoring and measuring changes in key soil parameters will be important not only for soil health, but also could connect to monitoring of water quality, air quality or other policy targets. Integrating this monitoring across multiple policy objectives is essential for effective and joined-up policy and practice.

Circular economy

Defra briefing

The concept of Circular Economy emerged in the 1970s from the observation that it takes fewer resources to repair or recycle existing products than to manufacture new ones from primary raw materials (Stahel, 2016). In 1992 during the ‘Earth Summit’, the concept of CE was put forward as a means of reaching a sustainable economy. The idea of CE has been gaining momentum recently, as a policy avenue for addressing the major environmental and climate change challenges that we face (Geissdoerfer, 2017).

In 2018, the UK government published its ‘25-year plan’ for improving the environment. It outlines that CE principles will be supported by the key goals of using resources from nature more sustainably and efficiently, and minimising waste (Defra, 2018b). The plan undertakes to ‘Make sure that resources are used more efficiently and kept in use for longer to minimise waste and reduce its environmental impacts by promoting reuse, remanufacturing and recycling’ (Defra, 2018b: 83).

In the face of the current climate and environmental challenges, there is increased momentum to move towards a more circular economy, particularly in terms of nutrients being returned to the food chain or used to generate other resources (such as energy) rather than lost into the environment. This can improve productivity by reducing waste and stimulating innovative ways of recycling nutrients. A visual comparison of nutrient flows under linear and circular systems has been provided by the United Nations Economic Commission for Europe (UNECE, 2021), illustrating the multiple benefits of ensuring that nutrients are re-used rather than wasted as environmental pollution (Figure 2). While the image illustrates the case for N, the same principles apply for recovery of nutrients more generally.

Figure 2: Simplified comparison of linear and circular economies for N in the agri-food system (UNECE, 2021).

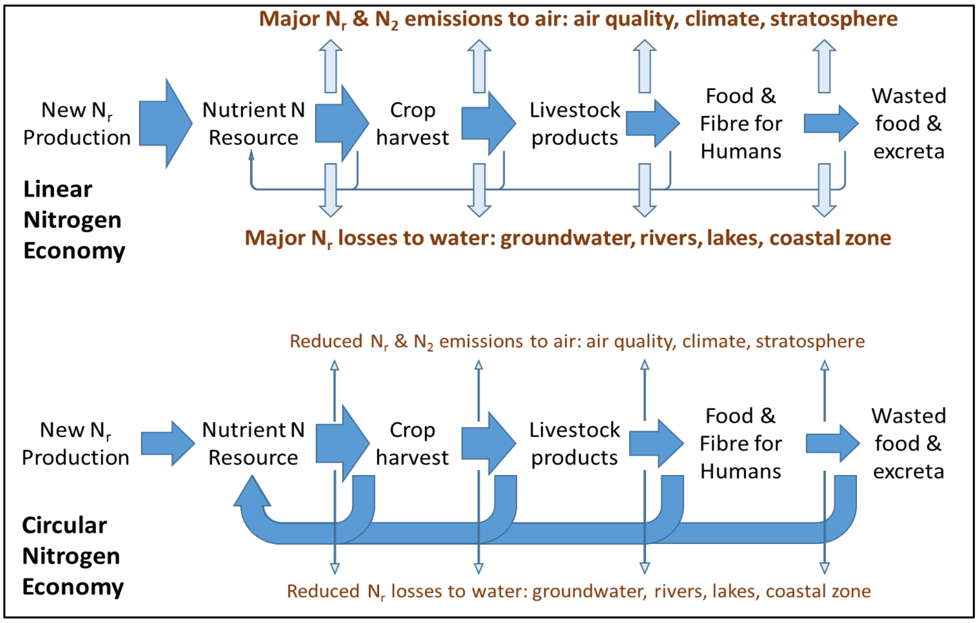

Figure 2 description: a flow diagram showing the difference between a linear nitrogen economy and a circular nitrogen economy. This includes crops harvested, livestock produced, food fibre for humans, wasted food and excreta. In the circular nitrogen economy, the nitrogen losses to water and emissions to air are reduced.

Concerning nutrients, the UK Resources and Waste Strategy contains the most explicit references to a CE and includes specific measures such as using digestate from anaerobic digestion (AD).

The Green Gas Support Scheme launched by the Department for Business, Energy and Industrial Strategy (BEIS at the time) at the end of 2021 is set to further boost AD over the next 4 years until 2028, across the country. The scheme will lead to a significant increase in the amount of digestate produced, which will need to be managed effectively to minimise contaminants, and ensure farmers can source it, store it, and apply it to land in ways that optimise nutrient use efficiencies while minimising nutrient pollution.

Questions to NMEG

1. Case for public support: How widespread are AD and composting processes in the UK? Do you have a view on the relative merits of these technologies and on whether government should play a part in supporting any of them (such as government R and D funding for emerging technologies), or whether the market will effectively stimulate the most sustainable routes and bring prices down?

2. Environmental safety: Can recycled nutrients be a more sustainable alternative to inorganic fertilisers? What are the environmental risks of nutrient recycling and recovery? How can we set limits which would be acceptable for environmental protection, while being sufficiently pragmatic and practically achievable to stimulate the market for AD?

3. Usability for farmers: What is the predictability of nutrient concentrations and nutrient availability of fertilisers made from waste? What are the benefits of the minimum nutrient, organic carbon and dry matter limits in EU regulation – should we have these limits in UK regulation?

4. Market development policies: In addition to resolving the issues which help make it a more attractive product, how else can we ensure that digestate acquires market value? How can we best prevent digestate being disposed of as waste, and ensure it is managed and spread in accordance with soil and crop need, as an attractive alternative to inorganic fertilisers? Taxation or legislation could be deployed but are cumbersome tools. What might be alternative ways to valorise digestate and other organic waste fertilising products? What drivers and barriers do you foresee?

5. Composting challenges: How can we bridge the gap between compost from green waste and compost containing peat? What replacements are available for peat (for example, wood chips) and are there barriers to obtaining these replacements?

NMEG discussion

Principles of organic materials processing for nutrient management

Until agricultural developments over the past century led to the geographic separation of livestock from arable farming across much of England, its agriculture relied more on a circular nutrient economy: organic materials such as livestock manures, biosolids and food-based materials rich in key nutrients N and P, were returned to land to fertilise crops (Yuille et al., 2022). As nutrients represented scarce resources at the time, there was also a stronger motivation to reduce nutrient losses to the environment, although it must be acknowledged that nutrient losses from many farming systems would still have been substantial. With the advent of inorganic fertilisers, there has been less motivation to minimise nutrient losses.

The idea of the circular economy is closely linked to a re-evaluation of what is meant by the terms waste, residue and resources. The agronomic research community has long objected to the description of manure as an ‘organic waste’, insisting that it should be seen as a valuable resource. Similarly, member states of the UNECE and UNEP have recently identified the concept of ‘nutrient waste’, as the sum of all losses to the environment which is equally a waste of resources (UNECE, 2021). It is important to recognise that in current terminology, the meaning of ‘waste’ also varies by context (for example, food waste, municipal solid waste, wastewater, nutrient waste and waste of money).

A wide range of organic residues and waste materials are produced as by-products from industry (for example, food, beverages and paper), agriculture and households (Bijmans, 2011). The use of existing and emerging technologies could accelerate re-integration of such ‘wastes’ as resources representing a source of carbon, nutrients (N, P) and energy to support a circular nutrient economy (Rosemarin et al., 2020).

Two centuries ago, there was already agronomic debate on whether to use manures immediately or to let them decompose prior to use. Erasmus Darwin (grandfather of Charles) argued for immediate incorporation of fresh manure into the soil to prevent the loss of ammonia and carbon that results from decomposition and is wasted in the wider environment (Darwin, 1800). While there are risks from storage and decomposition of manure and other organic residues, these also offer current opportunities, especially in timing the application of nutrients to when they are most needed by growing crops. The 2 main strategies for managed decomposition are AD and composting.

AD is a sequence of processes that involve the decomposition of organic matter by microorganisms in the absence of oxygen, turning it into biogas (and heat, if the biogas is used to generate electricity) and liquid ‘digestate’ residue. Biogas is a mixture of carbon dioxide (CO_2) and methane (CH_4) and other trace gases. While the resulting digestate can act as a fertiliser that is rich in readily available N, the high ammonium content poses an increased risk of loss by NH_3 volatilisation if strategies are not used to reduce this risk, for example, use of trailing hose or injection to apply digestate to land. By definition AD is a closed process allowing recovery of CH_4, CO_2, NH_3 and other dissolved nutrients.

Composting involves the decomposition of organic matter in the presence of oxygen, which can be a standalone activity with a range of organic resources. Aerobic processing has the potential to release more nutrients during the decomposition compared to AD, including NH_3, N_2O and N_2 emissions from denitrification which are emitted into the atmosphere. Because of these wasteful losses of N, composting may be considered as, in principle, less attractive for the circular economy than AD. Conversely, there is substantially higher potential for N and P losses following spreading on land of the digestate from AD compared to compost, unless mitigation or nutrient recovery strategies are implemented. This illustrates the importance of assessing nutrient losses at all stages of the chain, from the site of organic resource generation, through storage and processing to spreading on land.

How widespread are anaerobic digestion and composting in the UK?

AD has been widely used in the UK for the treatment of sewage sludge for over 100 years. However, its use for treating other wastes, residues or purpose-grown crops has developed since government published its first 'Anaerobic Digestion Strategy and Action Plan' (DECC and Defra, 2011) in order to generate more 'green' methane for domestic use and reduce the UK's reliance on energy from fossil fuels. A number of successive incentive schemes were launched, offering attractive rates for biogas generation which led to rapid growth in the AD sector, with the number of plants increasing from 68 (2011) to 140 (2014) (Defra, 2015), and a corresponding increase in digestate available to spread on land. The most recent market report from the Waste and Resources Action Programme (WRAP) suggests there were 372 AD sites in 2019 and a gross estimated production of 7.5 million tonnes of digestate per year (Figure 3). This growth has been seen across all types of AD plants (farm, commercial industrial) (WRAP 2020a).

Figure 3: Sankey diagram of grossed estimated AD inputs and outputs (tonnes) WRAP 2020a.

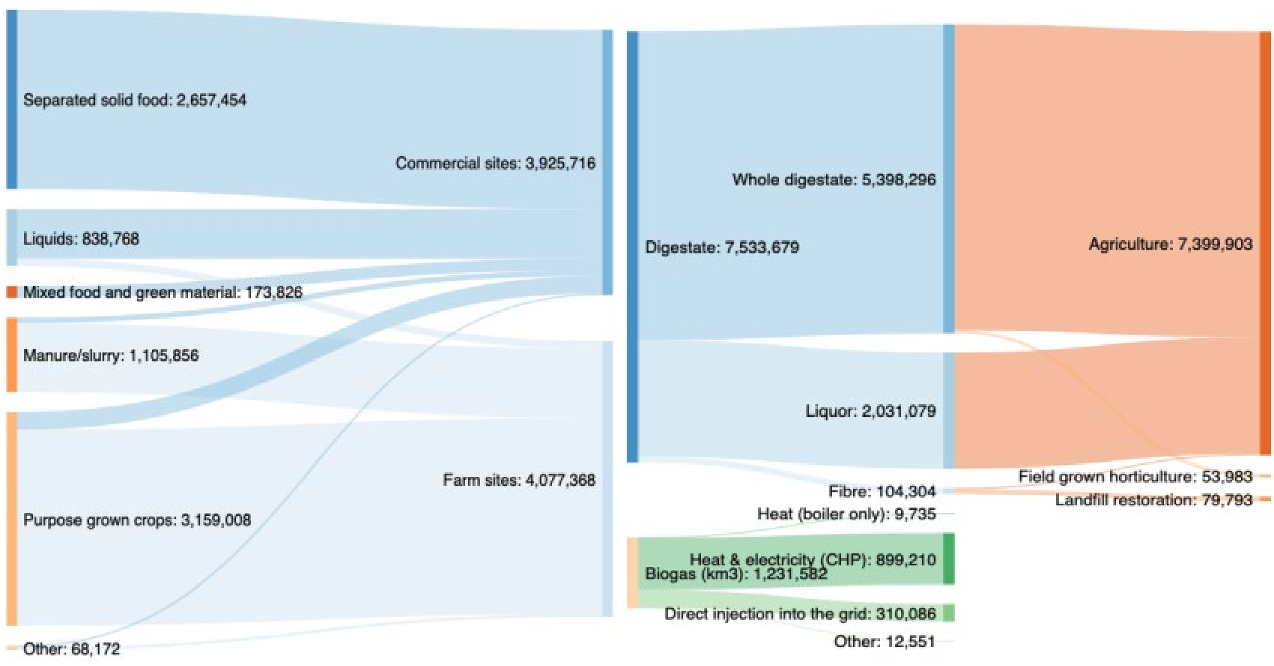

Figure 3 description: Sankey diagram showing gross estimated AD inputs and outputs. Most inputs come as purpose grown crops, the other half comes from solid food waste. The outputs of whole and liquid digestate nearly all go to agricultural land and are quantified at 7.39 million tonnes.

Composting in England (for which there is good market data) has remained relatively stable, but with a slight drop since 2010. In 2019 there were 272 operating sites whereas in 2010 there were 291. Of the 2 main types of composting (internal vessel composting and open windrow) windrow appears to be the most common, with only 7 vessel composting sites (WRAP 2020a). Production of compost in 2019 is estimated at around 2.6 million tonnes (see Figure 4 for a breakdown of input types and end uses). Assessment of the nutrient content of compost and losses during the composting process are not well published.

Figure 4: Sankey diagram of grossed estimated composting input and outputs (tonnes). WRAP 2020a

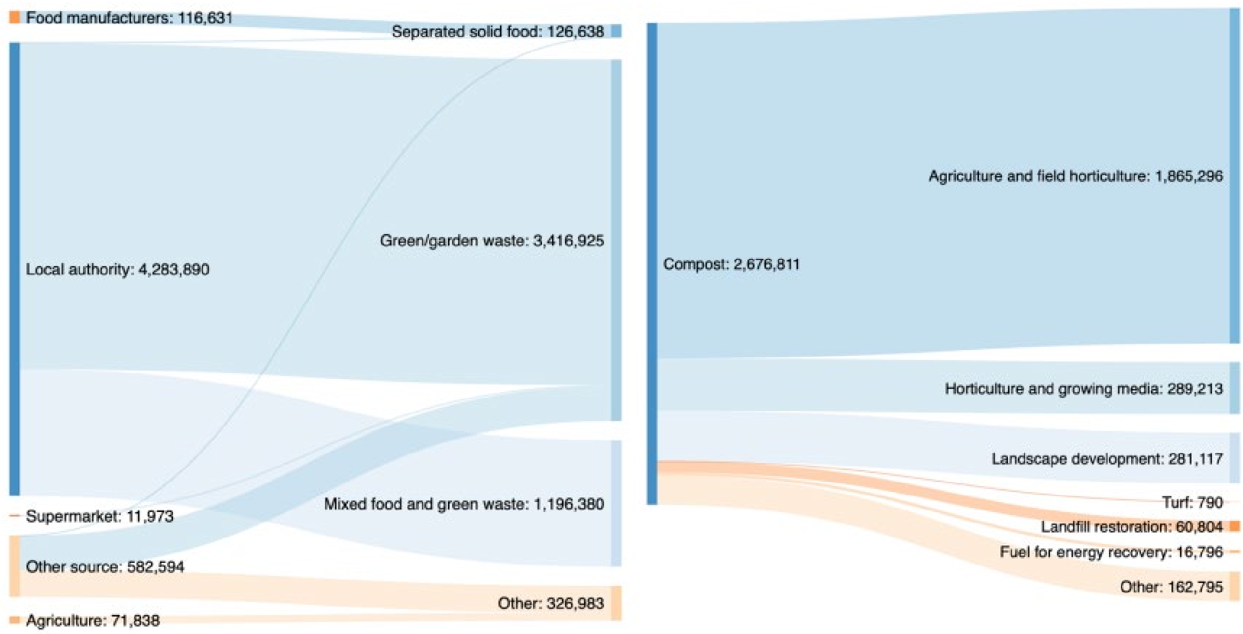

Figure 4 description: a similar Sankey diagram showing inputs and outputs of compost. The majority of compost comes from local authorities from garden waste. The majority of the output compost goes to agricultural land (1.86 million tonnes) and field scale horticulture (289 thousand tonnes).

Can recycled nutrients be a more environmentally friendly alternative to traditional fertilisers?

In the case of N fertilisers, production typically follows a linear economy with the Haber-Bosch process producing ammonia that is used to formulate ammonium fertilisers used to grow crops, which in turn feeds livestock and people, but with reactive N eventually being lost to the wider environment and denitrified to atmospheric N_2. Globally, N compounds are used with about 20% efficiency when considering the full food chain, and 35% for global cereal crop based NUE, with the rest being wasted while fertiliser manufacture uses around 2% of world energy (Sutton et al., 2013 and Omara et al., 2019). Such low efficiencies are also reflective of P use globally, with an estimated full-chain NUE of 12-20% and a crop NUE of on average 9% for grain (Sutton et al., 2013 and Brownlie et al., 2022). While these efficiency figures are low, they do not indicate that recycled nutrients can be used with more efficiency than conventional fertilisers. Recycled nutrients can however be considered more eco-friendly than fertilisers manufactured from energy-intensive processes due to their embedded carbon footprint. There is no simple way to make a fertiliser environmentally friendly: fertiliser products must have low embedded environmental impacts from production but also be applied in the right place, in the right amount, at the right time, and in the right form – the 4R approach[5].

The nutrient products from AD are here considered as a case study for how nutrients can be stabilised, combined and altered to provide more effective nutrient products. Many of the issues considered also apply to nutrient flows from non-agricultural sources, such as nutrient recovery from sewage and (potentially, in future) N oxides recovery from large combustion facilities (Sutton et al., 2013: Chapter 6).

Digestate and compost can both be applied directly onto fields to provide nutrients. In terms of efficiency, AD allows higher N recovery rates than aerobic systems, provided application methods and timing maximise crop N offtake and minimise the pathways of N loss through nitrate leaching and NH_3 volatilisation. NH_3 emissions are a potentially harmful by-product of digestate storage and following application to land, so AD facilities must be designed to avoid NH_3 emissions (for example, using digestate acidification) or incorporate ammonia 'stripping' technology to prevent pollution as well as to ensure optimal recovery and use of N.

The technology for NH_3 retention and recovery already exists but needs to be widely implemented to ensure circularity. Capital grants to ensure full nutrient recovery in AD offer the opportunity to accelerate change, while further market and legislative analysis is needed to better understand the barriers to incorporating recovered ammonium into mainstream fertiliser production. For example, the case for establishing a target for use of recycled ammonium in fertiliser products should be further explored. AD lends itself particularly well to the handling and recycling of wet food waste.

There are also opportunities to combine AD and composting. Solid-liquid separation of digestate provides a solid fraction which may be composted. Composting helps stabilise nutrients, but the current fleet of digesters in the UK tends not to have a post-digestion, aerobic stage nor to exploit the full opportunities for N, P and other nutrient recovery from

---

[5] 4R Nutrient Stewardship provides a framework to achieve cropping system goals, such as increased production, increased farmer profitability, enhanced environmental protection and improved sustainability. See **What are the 4Rs | Nutrient Stewardship**

digestate. Incentives and, or higher standards of operation could help to encourage this shift.

Use of unprocessed digestate

While digestate is a good source of crop nutrients and is currently often freely available to farmers as a by-product of biogas production, its farm use presents a number of practical challenges. Digestate typically has a low dry matter content (less than 5%) and is bulky and heavy, so can only be used within a short distance of the AD plant as transport is uneconomical, although this may become viable as the price of nutrients rises (Brownlie et al., 2022).

Digestate, depending on the feedstock used to make it, has variable nutrient content similar to unprocessed manures or slurries, making it difficult for farmers to calculate how much, especially if poor storage has led to volatile nutrient losses. This implies a need for regular analysis of digestate nutrient content, as already recommended for manures in the RB209 guidance.

Appropriate application techniques are also needed. Surface application of digestate can lose a substantial fraction of ammonium N via NH_3 volatilisation, indicating a need for specific measures to avoid this risk, such as bandspreading, injection into the soil or acidification prior to application (UNECE, 2021).

Options for basic processing of digestate

In order to encourage greater adoption of digestate by farmers as a substitute for highly predictable inorganic fertilisers, there is obvious benefit transforming it into a more standardised, predictable and easy-to-handle product, more easily transportable from AD plants to farms, and easier to spread. One process explored by manufacturers is pelletisation: dewatering and compacting the solid fraction of digestate into small pellets comparable to inorganic fertilisers (WRAP, 2020b). While certain processing techniques may add value, this does not mean those products would be any more nutritionally effective than basic digestate spread correctly. Solid pellets would likely not contain the N required to make them comparable to other high nitrate-based fertilisers. Nutritional alterations to these solid fractions would however make them more comparable.

Advanced processing of digestate

Nutrient recovery in the circular economy can be part of ‘value-added’, complementing the economic value of AD biogas production. Whereas small scale facilities may focus on local use of minimally processed digestate, the philosophy is well fitted to large scale operations, as illustrated already by sewage treatment plants becoming the fertiliser factories of the future (currently demonstrated in Copenhagen which removes N from wastewater) (Ragn-Sells 2022).

N recovery in such systems is by ammonium stripping’ where NH_3-rich liquor is depleted of NH_3 either by degassing or by precipitation as an insoluble salt such as struvite (ammonium magnesium phosphate) (UNECE, 2021). The collected NH_3 is then typically combined with an acid to make an ammonium salt such as ammonium nitrate or ammonium sulphate. Where the regulatory environment allows, the ammonium salts can be sold and combined with fertilisers produced from conventional N fixation (Haber-Bosch). In this way, it is possible to envisage regulations, incentives or business initiatives to sell fertiliser products with a minimum content (such as 20%) of recovered N[6]. This approach follows the model used in petrol for vehicles, which now contains 10% ethanol in the E10 standard. A similar approach could be taken for P and other nutrients.

Processing technologies can be very energy intensive, increasing a product's carbon footprint. This highlights the need for further innovation for low energy approaches to reduce costs and footprint, as well as develop economies of scale. In addition to the immediate environmental advantages of moving to a circular nutrient economy, there are long term economic advantages, such as reducing dependence on imported nutrients that are vulnerable to substantial price variations in response to geopolitical events. Given the pros and cons of nutrient processing and recovery, in the short-term policies and systems must be able effectively to deal with a full range of materials from the less to more processed, and seek to develop economies of scale by linking recovery from a wide range of organic resources, including biogas production, sewage, municipal solid waste.

It remains a matter for further analysis to see how best to mobilize such change. For example, regulation of biogas and other organic matter processing facilities could be used to ensure that they incorporate technologies which optimise reuse of nutrients and minimise NH_3 emissions. There might be scope for better linkage with existing pollution control or environmental permitting regulations, to make it a requirement to recycle available resources as part of permitting. At the same time, a wide range of economic incentives including policy support (investment grants and regular payments for beneficial practices on farms) could help accelerate change.

Reducing environmental risks of nutrient recycling and recovery

The production of digestate as a by-product of biogas generation schemes such as the Green Gas Support Scheme will need to consider the full system, to ensure optimal processes for efficient use of all resources involved, and at all stages of the organic resource chain. Rules or standards should prevent large amounts of material from being generated and applied without adequate land capacity for digestate nutrients to be taken up by crops.

[6] For an example see work by the JRC on the 'RENURE' project available at https://publications.jrc.ec.europa.eu/repository/handle/JRC121636

Organic N, P and C present in digestate are typically more bioavailable than the raw materials, and can drive significant ecosystem changes if they flush from land to water (Mackay et al., 2020). If the use of organic materials is to increase, controls on their use to reduce the risk of flux to adjacent waters, and monitoring, are required.

Another environmental risk is the high contaminant levels that have led farmers to turn away from digestates and compost after trying them. Tighter regulation of contaminants in end products would make them more attractive products for farmers. A common contaminant found in digestate is plastic, which can arise from package food waste feedstocks or other non-target materials being mixed with input feedstocks.

There is still a great deal of research required to fully understand the effects of plastic decomposition in the soil, whether it is 'biodegradable' or not: soluble compounds from biodegradable plastics are an emerging concern. Several ongoing research projects on microplastics in soils may help to answer this and other questions on the plastic contamination coming from digested or composted products. Setting the standard for what makes a plastic biodegradable is key. Other contaminants need to be evaluated in addition to plastics, for example, eco-toxins and pathogens that present risks to the wider soil and water environment.

How can government support the development of the market for recycled nutrient products?

The Waste and Resources part of the Environment Act 2021 includes provisions to ensure households have a weekly separate food waste collection, and for businesses and other organisations to arrange the separate collection of recyclable materials. The Resources and Waste strategy commits to 'work towards eliminating food waste to landfill by 2030'. Food waste and green waste collections will therefore be increased over the coming years, resulting in a larger volume of organic material available for nutrient recovery (via composting and AD). It is anticipated that the increased, separately collected food waste will largely be sent to anaerobic digestion. This has the best environmental outcomes: by removing food waste from landfill (leading to carbon savings), recovering energy through biogas extraction and recycling food waste through the production of digestate derived fertiliser. Under current plans, in England, it is anticipated that the increased, separately collected food waste, will largely be sent to anaerobic digestion generating an increase in AD waste feedstock. The latest publicly available evidence indicates that from 2024, there will be an increase in food waste collected from households and businesses equal to 1.71 million tonnes (Defra 2020). The resulting increase in food-waste derived digestate available to spread to land represents both an opportunity for farmers, and for advancing the circular economy, but does represent risks to the environment if not managed appropriately.

This Waste and Resources Strategy, however, focuses primarily on post-farm gate processes rather than on-farm processing of materials. There is no reference to the CE as a concept in the Clean Air Strategy. Similarly, current Defra proposals identify targets for reduction of N and P in water pollution and particulate matter air pollution (which contains a substantial N fraction) (Defra, 2022b), but make no reference to the nutrient cycles that link these threats, nor the opportunity offered by embracing a circular nutrient economy to deliver synergies and help overcome barriers to change. This is something government should be doing to ensure more holistic policy making.

The regulatory regime for fertilisers in Great Britain is outdated and in need of modernisation. It chiefly sets standards for inorganic mineral fertilisers rather than organic or organo-mineral fertilisers. Defra has a role in ensuring that there are no regulatory barriers to selling fertilisers made from recycled nutrients from all sources, so long as product standards are met and nutrient application guidance, rules, tools and techniques are adhered to. Defra should consult with industry and the public to determine the best policy proposals to strike a balance between promoting innovation and smoothing the route to market, while setting appropriate standards for environmental protection.

When a new market development aligns with social goals, there is a role for government to support and speed up confidence-building and investment in responsible markets by creating a propitious regulatory environment, and supporting both producer and consumer confidence through mechanisms such as quality assurance systems. The government must clearly indicate its direction of travel, to help producers feel confident that there will be a future market worth planning for and investing in, with sufficient demand for proposed products.

To support product quality, strong targets for N, P and C content and availability in marketed digestates and composts could be set in advance through government working with technology experts and scientists. There is also scope for government to invest more proactively in science and technology or consider joint industry-public sector partnerships to fund innovation, knowledge transfer, and demonstration opportunities.

For farmers to use these new products, it is essential that they know exactly what nutrients are in them, and how quickly they will be released. This should not just be with regard to N but also with regard to P as more recent research has shown (Masso et al., 2022) There is currently much variability depending on feedstocks, and AD plants do not provide regular nutrient content analysis to help inform the farmer, many rely instead on generic historic values. Better analytical techniques are required to reliably provide this information, and regulation might usefully mandate the provision of this data by the manufacturers.

Product variability is also caused by failure to follow industry good practice, among some suppliers. For example, farmers have reported that sometimes digestate is delivered whilst it is still at a high temperature straight from the AD plant, risking scalding crops. These incidents are anecdotal and should be rare if product comes from well-known and certified suppliers. Compost consistency can also vary depending on the time of year, from very woody to smooth and green. Better government oversight of the sector could help ensure good practice is systematically followed and that standards are kept up to date (for example, checking PAS100/110 and the Quality Protocols).

How can recycled nutrient produced acquire a market value and become an alternative to conventional fertilisers?

A positive approach to encourage wider use of recycled nutrient resources would be to provide improved guidance on how to use them to best effect. This would help farmers incorporate it into their nutrient management plans, through updates to RB209 and MANNER-NPK or new tools, and reduce inorganic fertiliser use accordingly. Explaining the co-benefits of carbon-rich organic materials, compared with inorganic NPK, could also help.

In theory, taxation could be applied differentially so that the retail price of different fertilisers could better reflect their environmental footprint, internalising their externalities. This would further push up the cost of inorganic fertilisers derived from a CO_2-intensive manufacturing process, and make alternatives comparatively more attractive, however such action could be seen as too severe an approach in a time of significantly increased prices for other reasons. Alternatively, fertiliser manufacturers could be compelled to include a certain minimum proportion of recycled nutrients, to better valorise and provide a ready market route for them, and to encourage ammonium-stripping from AD. Making inorganic fertiliser very expensive or scarce, or making recycled N compulsory to some extent in supplied N, may lead to a positive change in farming systems, as already illustrated by the price increase in fertiliser associated with the war in Ukraine. Knock-on considerations are also important: moves should avoid supporting maintenance or increase in livestock production driven by nutrient demand, as a result of incentivising greater commercial capture and recycling of manure and slurries. While manures may be free on farm, they result from livestock production which also has a significant GHG footprint, which ideally should be better reflected in the value of meat and milk as well as waste products.

Clarification of the spreading rules for organic materials is important in light of the debate on Farming Rules for Water and the need to meet new and ambitious targets to reduce N, P and sediment loading to waters by 40% under the Environment Act. Farmers should be able to know when they can spread digestate legally and how they should build it into their farm nutrient budgets and nutrient management planning.

Concluding remarks

Creating a circular nutrient economy should be a high priority in governments agendas, across the UK. The agri-food sector needs to minimise losses of nutrients throughout the production and application chain, but also value the recovery and re-processing of nutrients on a larger scale. The principles of the circular economy can help mitigate further GHG emissions through reduction of energy-intensive production methods, while also emphasising recovery and reuse of those essential nutrients for societies benefit.

Key points:

1. There are no clear and simple answers to which method of recycling nutrients is best. Anaerobic digestion typically increases nutrient recovery, but the resulting product tends to be at higher risk of loss on application to the land. Composting results in more losses during processing but generally lower risk of loss on application to land.
2. Recycled nutrients from organic materials and other nutrient recovery techniques have potential to reduce use of higher carbon footprint fertilisers and also be blended with traditional sources of nutrients to help support sector-wide transition to more sustainable fertilisers.
3. Government should encourage a regulatory framework and policy pathway for nutrient manufacturers and farmers that promotes much greater nutrient recovery and quality assurance of products to build consumer confidence.

Climate change, nutrients and the UK's Net Zero target

Defra briefing

Climate change is accelerated by GHG emissions, which are produced both by natural systems and by human activity (Fawzy et al., 2020). Natural systems involved in the release of GHGs include: forest fires and ocean generating CO_2; freshwater ecosystems and high latitude permafrost emitting CH_4; and volcanic eruptions causing both CH_4 and CO_2 to be released directly into the atmosphere (Yue and Gao, 2018). In terms of human activity, referred to as 'anthropogenic emissions', there are 5 main economic sectors responsible for GHGs globally: energy, industry, buildings, transport and AFOLU (agriculture, forestry, and other land use) (Lamb et al., 2021).

Agriculture is a source of 3 GHGs: N_2O, CH_4 and CO_2. In 2019 agriculture in the UK accounted for 11% of total GHGs emitted, composed of 32% N_2O, 54% CH_4 and 1.7% CO_2 (National Statistics, 2021b). It should be noted that agriculture is however not a sole emitter, it is also a sector where sequestration occurs simultaneously. N_2O and CH_4 account for 90% of agricultural emissions. These are both potent GHGs but have very different average atmospheric lifetimes, of approximately 114 years and 12 years respectively, while CO_2 is the most persistent GHG (BEIS, 2020).

N_2O is the most potent of GHGs arising from agriculture, with warming effects 273 times greater than CO_2 (Defra, 2022a). The main sources of N_2O are the application of fertilisers (both inorganic and organic) the storage of manure, decomposition of crop residues and returns of excreta to soil by grazing livestock. In addition to these direct sources, indirect sources such as NH_3 emissions, nitrate leaching and N deposition also contribute to the total N_2O emissions. The production of inorganic fertiliser is highly energy intensive and has been estimated to account for 1.2% of global GHGs from human activity (Wood and Cowie, 2004), and over half of total energy use in agriculture (Woods et at., 2010). Organic manures from livestock also have a significant GHG footprint, as livestock have been estimated to contribute around 14% of anthropogenic GHGs (Gerber et al 2013). Sound nutrient management therefore has an important role to play in reducing GHGs.

What does Net Zero mean for UK agriculture?

At the 2015 "COP 21", the UK signed the Paris Climate Agreement, a legally binding global climate change agreement setting a framework to reduce global warming to well below 2°C, compared with pre-industrial levels (UNFCC 2021). In 2019, the UK government amended the Climate Change Act committing the UK to 100% reduction in Carbon emissions, relative to 1990 levels, to be achieved by 2050. In 2008, the UK's Climate Change Act introduced domestic legislation setting out the system for five-yearly carbon budgets. The UK's latest nationally determined contribution (NDC) as part of the Paris Agreement, published in September 2022, commits to reducing GHG emissions by at least 68% by 2030 (compared to 1990 levels) (BEIS, 2022).

The Committee on Climate Change (CCC) has projected how savings could be delivered in agriculture, presented most recently in their Carbon Budget 6 report (CCC, 2020). The CCC presents a stark and challenging decarbonisation pathway for agriculture over the next 10 years (Figure 5), with emissions reductions from 55 to 35 million tonnes CO_2e by the end of 2050 in the UK. This represents a reduction of about one third from current levels. We can expect targets to become even more challenging when emissions from peatland are accounted for in the inventory, and targets are re-addressed in line with the recently increased Nationally Determined Contribution (NDC) targets (BEIS, 2022).

Figure 5: CCC Balanced Net Zero Pathway for Agriculture (after their Sixth Carbon Budget Report, Dec 2020) Sixth Carbon Budget - Climate Change Committee (theccc.org.uk)

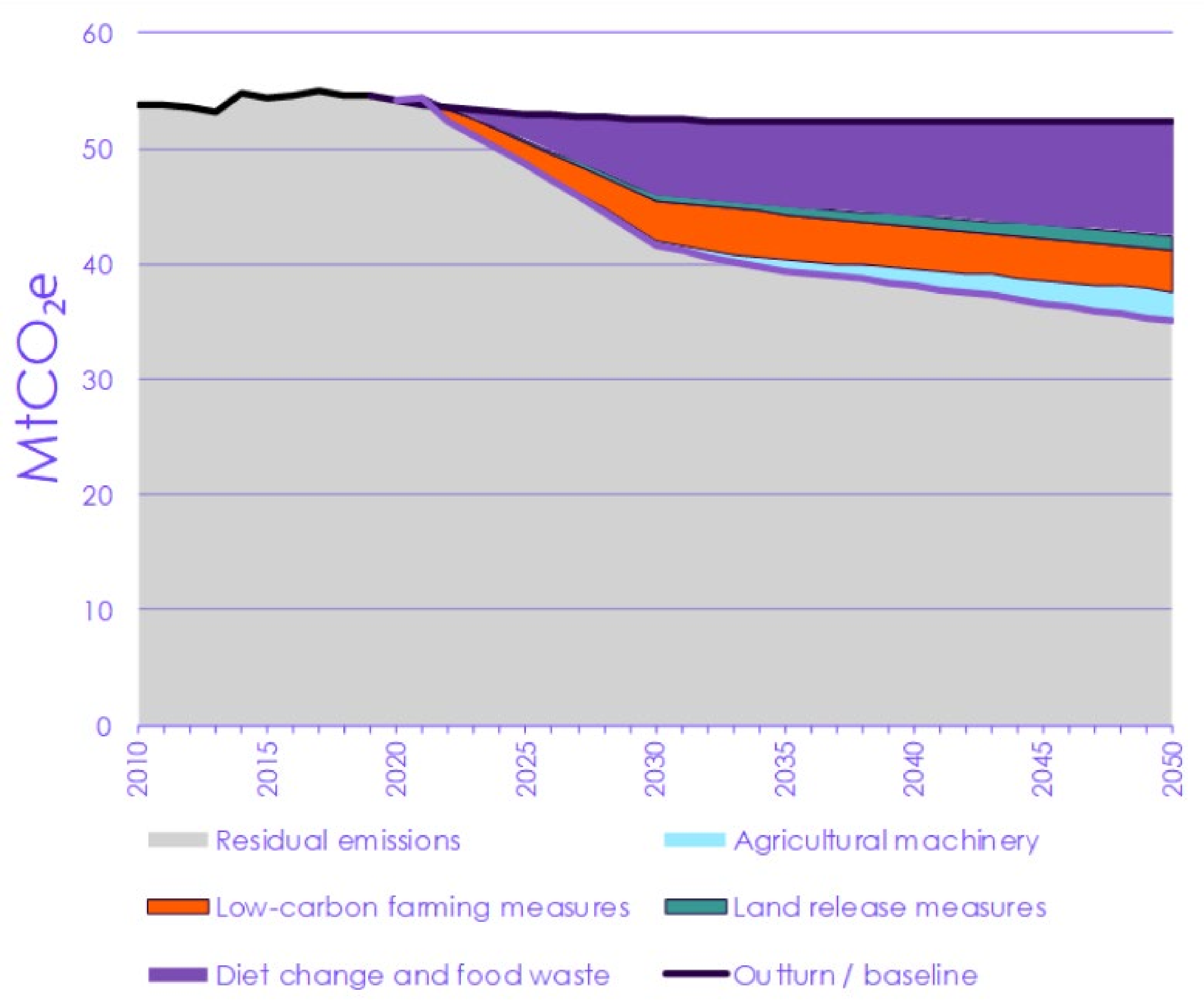

Figure 5 description: a graph showing the carbon emissions in MtCO2 on the y axis of the UK from 2010 to 2050 on the x axis. It breaks down the contribution of various measures such as low carbon farming practices, land measures and dietary change measures. The greatest gains will be made from dietary change and food waste.

How is the UK proposing to reach Net Zero?

In October 2021, the UK government published its 'Net Zero Strategy: Build Back Greener'. It outlines the UK's plan for a transition that will take place over the next 3 decades up to 2050. A phased approach is deemed necessary, aiming to reduce emissions across each sector of the economy including power, fuel supply and hydrogen, industry, heat and buildings, transport, natural resources, and GHG removals. In agriculture, the government in England plans to support low carbon farming practices through new ELM schemes, such as

- the Sustainable Farming Incentive and ELM
- to help farmers be better equipped through the Farming Investment Fund
- incentivise research into new technologies through the Farming Innovation Programme

A similar mix of incentives, investment funding and regulatory measures are under active development by the devolved governments in Wales, Scotland and Northern Ireland.

Questions to NMEG

1. What policy levers can the government use for reducing climate emissions at the farm level?

2. How could carbon audits be integrated into business decisions?

NMEG Discussions

What (nutrient-related) policy levers can the government use for reducing climate emissions at the farm level?

Policy levers should ensure benefits across all aspects of the environment and not inadvertently support systems that contribute to the release of excess nutrients in other forms (such as water and air pollution). It is important to ensure that policies aimed at reducing one pollutant pathway do not increase losses by another, known as ‘pollution swapping’. Focusing on improving overall nutrient efficiency while reducing nutrient losses offers multiple win-wins for climate, air quality, water quality, biodiversity, soil health and the economy. A clear vision of the scale of the challenge and desired destination, agreed with stakeholders, is essential to ensure coordinated action.

Specific nutrient management measures can be identified to reduce GHG emissions from agriculture; many of these have potential to deliver benefits for other Defra environmental goals and have therefore been discussed in previous chapters of this report.

Options include the use of nitrification inhibitors, optimal timing and rates of fertiliser and manure applications better matched to the plants’ needs and conditions, the substitution of fertiliser N with legumes and, or manure N, and keeping livestock off land that is waterlogged. At farm level, cover and catch cropping have benefits for both soil health and reduced nitrate leaching (an indirect N_2O source), soil erosion and fluxes of C, other N forms, P, and sediment to water. In the short term this may only allow around a 10% reduction in other N inputs (of 20 to 30 kg readily available N/ha) depending on the species used, but further benefits may be seen in the following years. As a long-term practice, these benefits may accrue as soil organic matter decline is lessened and soil fertility better maintained. Impact on the immediately following crop yield is generally uncertain and depends on the cover crop mix, as well as soil and climatic conditions at establishment and destruction of the cover. Green cover crop residues can be a source of direct N_2O emissions which should also be considered and minimised through appropriate practices.

Measures under consideration to improve water quality, including an increase in the regulatory baseline for nutrient management standards, would also yield significant benefits towards Net Zero. The use of nitrification inhibitors has the potential to contribute to N_2O reductions via mitigating direct N_2O production and reduced nitrate leaching, although there are some uncertainties in respect of their efficacy which are discussed earlier in this report (see the chapter on air). Air quality-focused efforts to reduce NH_3 emissions, oxidized N emissions (NO_x, N_2O) and N_2 will contribute to coherence in reducing overall nutrient losses, so that a larger share of N inputs is available for food production (UNECE, 2021). Reductions in NH_3 emissions will also result in reduced indirect N_2O losses following N deposition.

Turning to policy instruments, the basic mix of regulation to set and enforce acceptable standards of practice, investment aid to support new or enhanced infrastructure associated with meeting these standards, payment schemes to encourage best practice or innovations going beyond the regulatory baseline, and advice and information to support all of these levers, are relevant for nutrient management measures targeting Net Zero. The pros and cons of some key options which simultaneously deliver benefits to air, water and soil quality have been discussed in previous chapters of this report – these include nutrient management budgeting and planning as either a requirement of regulation or a paid element in ELM (see page 27), also advisory support and investment aid to improve manure management and encourage its use in place of inorganic fertiliser (see pages 19 to 21 and 35 to 37).

Grants and loans for improving infrastructure such as slurry stores, to allow more flexibility for the optimal timing of slurry application (so as to reduce risks of applying when denitrification and, or, leaching are most common), could be made subject to mechanisms such as conditions specifying 'nutrient commitments', for example, the maximum allowable nutrient loading limits for the land on which slurry will be spread. This would aim to better manage the risk that increased slurry storage capacity might otherwise incentivise or 'lock in' unsustainably high livestock numbers on a holding, rather than simply improving the timing of slurry applications to ensure reduced risk of losses.

There is evidence that voluntary incentive schemes, whilst often seen as a central policy instrument to improve agri-environmental outcomes, have limited ability to achieve major shifts in practice as the uptake of more significant and impactful options is often low and farmers tend to opt for management practices with which they are already familiar. By contrast, focusing funding explicitly around the concept of technical innovation and linking advice, group facilitation and management payments within a collective 'project', can provide a stronger incentive for significant change (as has been seen in Ireland's use of the European Innovation Partnership approach for environmental benefits – Jones et al., 2019).

Regulation may target supply chain partners beyond the farmgate. Regulation and standards for food manufacturers and retailers may exert a more effective 'pull' on farmers than measures targeted directly at producers. Monitoring sustainability standards through the supply chain may be supported by carbon and N audits or similar tools (including P full-nutrient and sediment audits). Nevertheless, transparency is not always apparent in supply chain actions, which may encourage 'greenwashing' (claiming benefits which do not actually arise in practice).

Potential policy incentives include market-based instruments which aim to ensure that the full costs of inputs (including environmental damage) are shouldered by the producer, supply chain actors and consumers. Establishing new food production standards with manufacturers and retailers may require their farmer suppliers to charge higher prices for these products to fund on-farm infrastructure or practice changes. Alternatively, taxes or charges could help to internalise some externalities of more environmentally damaging production methods (such as the notion of carbon taxes applied to conventionally farmed food), generating revenue that could be used to support shifts away from these methods. In practice, there are very few examples of environmental taxes applied to agricultural produce, because of the difficulties inherent in establishing a cost-effective, acceptable and transparent approach. Such options (new food standards or taxes) would impact consumer demand for products[7] and could face competition from imports produced to lower standards.

More broadly, the effectiveness of any intervention, regulatory or voluntary, depends on the accompanying support and learning package offered when a new scheme is rolled out, which needs to be sustained alongside it. Effective coordination with, and resourcing of, relevant delivery and enforcement bodies (for example, the Environment Agency, Natural England and the Rural Payments Agency) is essential in ensuring that policy is delivered in the way that was intended and is actively and effectively enforced. In the general sphere of policy seeking to reduce environmental pollution in England, under-investment in effective delivery and appropriate enforcement has been a significant issue, in recent years. Different approaches are needed where farmers are given warnings first, possibly followed up by actions, before resorting to fines or legal action as a final measure (similar to the SEPA model used in Scotland). The Agricultural Transition plan included a commitment to move in this direction in England.

How could carbon audits be integrated into business decisions?

The climate change challenge appears currently to be generating enthusiasm for carbon planning and innovation among farmers and land managers; this offers an opportunity to harness that momentum, especially in a context of sharply increased fertiliser and fuel costs. The carbon audit tools market is booming, with a wide range of products offering different functionality and based on different assumptions and calculations which are not always transparent to the user (Taft et al., 2018). The estimates of the GHG impacts during the refinement and commercialisation of 'carbon footprinting' have been obtained and incorporated by organizations distinct to the scientific community (Weidema et al., 2008), but the science behind the tools is still emerging, so there is limited consistency among them.

To avoid pollutant swapping, it is important for carbon tools to be used alongside, or modified to incorporate, parallel N, P and sediment audits, along with advice on biodiversity improvements. Tools such as FARMSCOPER (Collins et al 2016 and Zhang et al 2017a, 2017b) can simultaneously estimate the likely emissions of these contaminants to air and water, in response to various suites of on-farm nutrient loss mitigation measures: this is a particularly valuable approach.

---

[7] Increasing costs for similar products via standards might differentially increase prices on those production methods which don't already meet the standards; and taxing those with the most negative environmental impacts will also do this, so demand may shift towards those products with lower impacts whose prices are less affected by such mechanisms. To apply these mechanisms to imports might be simpler for standards than for taxes (linked to WTO and other international trade agreements to limit border tariffs).

The carbon audit tools that are currently available provide insufficient levels of granularity to allow for robust farm-level business decisions to be made on this basis alone. The tools are useful to indicate, for example, emission hotspots at farm level, but they cannot yet reliably calculate the magnitude of emission reductions resulting from many changes in farm practice, as these are very difficult to quantify. Many carbon audit tools are commercial in origin so, while they are generally free for a farmer to use, they are not free for advisors. This may create barriers to providing effective support for their use. If carbon audit tools are to play a part in outcome-focused policies, it is essential for standards to be developed by government, to ensure consistent and meaningful metrics. PAS2050 standards are in place for carbon footprinting of individual products, so could perhaps be built upon to support a greater standardisation of audit tools.

Notwithstanding these points, the tailored advice and learning context within which such tools are used may ultimately have more impact on behaviour change than the specifics of the tools used.

There is a need for further development and mobilization of auditing tools for N – ammonium and nitrate specifically, also P and sediment, given the potential multiple co-benefits of integrated planning for climate, air, water, biodiversity, health, and economy, along with carbon audit tools. Such integration could have a great advantage in accelerating uptake of nutrient based measures for climate management, while at the same time contributing to reduced air and water pollution. Linking GHG and nutrient accounting tools more explicitly to farm-level key performance indicators may be another useful approach to improve engagement, using tools such as Farm Bench (run by the AHDB) and Measure to Manage (Business Wales, 2021).

As a final consideration, it is important to mention that policies and advice which support reduced waste in the food supply chain, and influence dietary choices by consumers, will have a major effect on reaching the ambitious target of Net Zero.

Concluding remarks

Key points:

1. Embedding the principles of reduced GHG emissions, and increased carbon storage and sequestration, into the mix of policy instruments promoting more efficient nutrient use and management in agriculture is a vital element in moving towards an effective sector contribution to the UK's Net Zero target.
2. Carbon auditing is a useful approach to evaluate farm-based actions that can improve the farm-gate GHG balance. These tools should however be coupled with N, P, soil and sediment balance monitoring to ensure carbon is not being increased without consideration of other environmental impacts.
3. The increased interest in carbon audit tools among farmers is a valuable trend upon which to build. Government should ensure consistency by setting standards to which the use of these tools can contribute (in consultation with the sector), irrespective of whether the tools themselves are publicly or privately initiated.

Conclusions and developing recommendations

Taking the broader view – key considerations

Over the 18 months of NMEG discussions, a wide variety of complex and interconnecting issues have been covered relating to nutrient pollution from agriculture. This chapter aims to draw together the overarching and common themes emerging from those discussions, to derive broader conclusions and recommendations to Defra on an enhanced future policy approach to nutrients in agriculture.

In light of the considerations set out in the earlier chapters of this report, NMEG believes there is an urgent need to take a holistic approach:

- embracing all nutrients, thus moving beyond the previous emphasis of policy on N, in particular to phosphorus, carbon and trace elements
- covering all relevant resources (soils, water and air, climate, also biodiversity and human and cultural capital) in a joined-up way, which can identify and minimise risks of pollution-swapping and seek synergistic changes in practice that benefit many sectors simultaneously
- considering the central role of farmer learning and the value of well-qualified, independent advice and information which accurately reflects the public interest in these issues, in helping to bring about enhanced outcomes
- recognising that different actors are aiming to achieve different results in their use and treatment of nutrients, over different timescales, and that these interests need to be brought together to build a more coherent response to policy

There are a number of over-arching principles established for joined-up environmental management, such as the 4Rs (right source, right rate, right time, right place), and the principle of keeping soil on the land, carbon in the soil and water in the field. However, nutrient interconnections need to be embedded in policy thinking and action in a more coherent way. In addition, policy must better acknowledge and build on positive change that is already happening in the farming and food sector.

Figure 6: A photograph of the NMEG group discussing cover crops and on farm nutrient management practices at Perdiswell Farm where NMEG member James Price farms.

Figure 6 description: a photograph of the NMEG group out in a field planted with cover crops. James Price is talking to the group about nutrient management practices on his farm.

The risks from nutrient pollution are not distributed equally across the country, (due to differences in the environment), therefore uniform standards may not be the most appropriate tool to deliver spatially appropriate outcomes. Examples of spatially tailored approaches include working within catchments to deliver water quality outcomes, targeting the most erodible soil types with permanent crops or cover cropping, reducing ammonia emission near to settlements and sensitive designated sites, and reducing stocking densities on those soils that are most vulnerable to compaction. The importance of high-quality, trusted advisors embedded within a particular locality and of integrated local knowledge also become apparent in identifying optimal strategies.

Our circular economy discussion also hinged greatly on ensuring that we do not repeat prior waste disposal mistakes – this requires understanding the broader challenges around achieving change. It is essential to recycle as many nutrients as possible in agriculture, but also to reduce the amount of nutrient-rich 'waste' generated by society, and the levels of contaminants within it.

If there is a central concept to the nutrient management challenge in agriculture, it is perhaps having a holistic vision for what sustainable land use means, and how this then maps onto the most appropriate management practices and nutrient loading rates that can be supported while protecting environmental goods, services and ecosystems which vary spatially across England. Henry Dimbleby's independent review on a National Food Strategy (2021) focuses on exactly this, in its recommendation to develop a land use framework for England.

Defra needs also to deal with trade-offs between pursuing short term environmental objectives and ensuring longer-term sustainability, in how land and nutrients are used. For example, it would be possible to significantly reduce nutrient loading by considerably reducing the scale of agriculture in England, but this would have negative implications for food security, which the group believes is also central to consider and protect.

It may take a significant time to see the positive results of changes in nutrient management practices, due to natural cycles. For example, in the case of water, if people stop releasing N into the environment today, it could take up to 40 years to see a difference in water quality within a chalk stream, due to the time lags between nutrient input to the land surface and its slow transfer to streams through the underlying chalk aquifer. However, in other contexts, such as in fast flowing streams draining through wet and steeply sloping upland landscapes, the benefits would be seen much more quickly. Stream chemistry is also likely to respond more quickly to mitigation efforts, but the biology may take more time to respond, especially where prior practices have led to local extinction of species. Lakes are likely to recover more slowly than rivers, given their capacity to accumulate and store contaminants within the lake sediments and biota themselves, and their much slower flushing rates.

It is also important to be aware that 'recovery' to a specific previous ecological assemblage may never be possible, and a new balance supporting a good mix of key species within an aquatic or terrestrial ecosystem may be a more feasible goal, particularly in the context of dynamic environmental conditions driven by changing climate and other factors beyond our short-term control. Building this understanding into policy expectations and monitoring approaches, so that lessons can be learned about what is possible and when, will be essential. This is a vital ingredient for maintaining engagement in policy delivery over the longer timescales that will be needed to successfully support and track environmental responses to mitigation efforts.

A lack of investment has been a systemic issue compromising government's ability to achieve better nutrient management in agriculture, for at least the past decade. The Environment Agency has suffered from this, as well as the water companies and those sector actors who could enable a swifter move to renewable energy and the capture and more precise reuse of nutrients from agricultural and domestic waste. Across the food system more broadly, to achieve a significant shift in the system it is essential to mobilise a greater sense of responsibility among the corporate bodies at the top of food supply chains. A central message of this report should therefore be about how impossible it will be to meet targets without significant investment in change from a nutrient perspective, across the whole food chain.

This range of interconnections was sketched out in a mind-map by NMEG as part of its 'field day' when members met face to face on a working farm, to consider its overall conclusions (Figure 7). It is this appreciation which underpins our emerging conclusions which follow, as well as the breadth and variety of NMEG’s 15 recommendations to Defra, which are given in full in the final section of this chapter.

Figure 7: Diagram showing key points grouped into 6 themes of action to improve nutrient management policy collated from NMEG views.

Figure 7 description: a diagram showing the key points from NMEG discussions. These are grouped under the headings of holistic thinking, innovative approaches, setting targets and data, working with farmers, dealing with trade offs and messaging and consistent approaches.

Emerging conclusions - An effective policy framework to achieve ambitious 21st century objectives

The central vision of this report has been to enable sector delivery on government's environmental targets. Separate expert groups have been working to agree exactly how these targets should be defined. For water, the 40% target for reductions in a range of key substances is very ambitious but necessary to meet broader environmental commitments.

Farmers need to go further than current 'best practice', for effective nutrient management that meets society's needs and challenges. Such significant change is unlikely to be achieved without considerable support from policy.

Advice is critical to nearly every target being discussed, yet its effectiveness cannot be assumed in light of the variable extent, quality and competence and coherence of current advisory provision to all farms across England. Agronomic, economic and environmental farm advisers may need re-training in how to achieve these ambitious targets, not just to continue aiming to meet previously promoted standards of best practice. Additional effort will be needed to reach those farmers who currently do not receive regular professional advisory support.

A coherent policy delivery model is needed which is clear, based on evidence, and sets out the responsibilities of each main group of actors and institutions. There are examples from other countries and in other topic areas of effective policy where government, agri-business and farmers organisations and other key stakeholders work in close partnership to develop a strategy and action plan, overseeing how evidence is gathered and analysed and agreeing how best to organise the response – we commend this approach.

Nevertheless, setting standards is essential and must be guided first and foremost by what is in the public interest. Defra has a responsibility to fulfil this role not only in relation to environmental targets but also in respect of those good practice standards that the sector works to (including the RB209 and similar documents and toolkits), and in respect of the standards expected of those providing advice to support delivery of targets and good practice, both at farm level and along supply chains. The development of market-driven provision cannot substitute for this role.

Defra should be identifying routes towards a more sustainable nutrient cycle, increasing nutrient use efficiency, recycling and recovering nutrients already in the system, and relying less on energy intensive non-renewable sources. Since 2021, fertiliser prices have risen significantly due to several factors but primarily the rise in natural gas prices and availability issues because of the conflict in the Ukraine. This current volatility raises the challenge of maintaining food security and energy security in a time of increasing shocks to global markets from a variety of causes. The UK currently imports a significant proportion of its N and P requirement, leaving it vulnerable to such conditions: moving to a more circular, home-grown supply system would greatly improve sector resilience.

Taking all these points together, the NMEG believes that **a national nutrient management Strategy and Action Plan would be a positive and logical next step for government** to develop, working in partnership with relevant stakeholders.

Recommendations

Recommendation 1

> The farming community and its many partners have made important progress in better understanding and tackling nutrient pollution over the past 2 decades. However, given the scale of environmental issues at stake, current action remains insufficient to prevent significant further damage and Defra policies need to address this shortfall.
>
> A strategic, long-term approach is needed to encourage more effective nutrient management and much higher nutrient use efficiency on all farms, and across all landscapes. We recommend the development of a national Nutrient Management Strategy to achieve this.

The farming community and its industry partners have made important progress in better understanding and tackling nutrient pollution over the past 2 decades. The positive momentum shown by farmers and land managers in response to environmental concerns must be harnessed and amplified further, to respond to the range of major nutrient-related challenges that remain. Significant changes in practice are required within and beyond the whole agri-food sector in order to meet the 25-Year Environment Plan and Net Zero targets. The constructive attitude that the agriculture sector has already shown in responding to Nitrate Vulnerable Zone (NVZ) Action Plans and the climate challenge gives confidence that, by working collectively with stakeholders and government and supported by good science, positive change can be achieved with co-benefits for the environment and for farm businesses.

Given the scale of the environmental issues at stake, current action remains insufficient to prevent significant further damage. To meet Net Zero targets while reducing environmental impacts of nutrient use requires further mobilisation across the agri-food sector. This will increase the adoption of best practice and consider further, more radical shifts in practices of food production, supply and consumption.

While we need to encourage higher rates of uptake of current, known mitigation measures, these in themselves will not deliver sufficient reduction in nutrient emissions to air and water, to protect and restore biodiversity in UK catchments, nor reduce emissions to a sufficient level to meet climate, soil, water and air quality needs. Defra-funded research suggests that 95% uptake of optimal mitigation measures included in FARMSCOPER, across all farms in England and Wales, would only reduce combined nitrate, P, sediment, methane, NO_x, and NH_3 emissions by around 20% at best, whereas for ecosystem recovery the reduction needs to reach an average of 40 to 50%, including significant reductions in total N as well as total P and sediment flux from land to water. Similarly, GHG emissions modelling on focus farms demonstrates that the maximum feasible reduction from best practice is around 20%. This falls far short of the GHG reductions needed to approach net zero, indicating that it cannot be achieved without also rethinking land use patterns and practices.

We recommend the development of a national Nutrient Management Strategy. A strategic, long-term approach is needed to encourage more effective nutrient management and much higher nutrient use efficiency on all farms, and across all landscapes. A clear vision of the scale of the challenge and desired destination, agreed with stakeholders, is essential to ensure coordinated action. Policy levers should ensure benefits across all environmental domains to ensure that policies and guidance aimed at reducing different pollutant forms or pathways are integrated and aligned so that they do not cause pollutant swapping. A clear focus on improving overall nutrient use efficiency and minimising losses to the environment offers win-wins for climate, air, water quality, biodiversity, soil health, agriculture and the economy.

Recommendation 2

Ambitious government targets for the environment must be supported by substantially increased public and private investment in innovation, mitigation and adaptation in the food system and sustainable land management if they are to be realised.

Many approaches require stronger support for capital investment, which can provide long term simultaneous rewards for efficiency, profitability and the environment.

Currently, insufficient resources (both public and private) are being released to finance the developments required. A wide-ranging integrated policy approach, ideally developed in partnership with food system actors, is needed, with a medium-to-long term package of measures and adequate financial commitment to deliver.

Recommendation 3

Policy development through meaningful co-design is a proven approach for delivering positive change: farming, land management, industry and other key stakeholders should be engaged throughout in agreeing and helping to promote the necessary sector shifts.

It is important to capitalise on the expertise of farmers and advisors in managing the landscape and natural resources, as well as the expertise of natural and social scientists, food system actors and policy makers, to identify the most cost-effective and practical approaches to achieve nutrient reductions. Advisors and farmers also have a key role to play in translating scientific knowledge into practical guidance and action through on-farm learning and collaboration. The development of ‘communities of practice’ spanning the academic, farmer, farm advisor, regulator, environmental NGO spectrum can foster relationships of trust and mutual respect, with increased positive environmental and business impacts. There is also scope for farmers to work constructively with a range of relevant business actors, forming 'green alliances' to promote best practice among spreading contractors for example. Or to enable local and regional manure exchange between arable and livestock production systems, to optimise its distribution and use.

Recommendation 4

A coherent suite of measures, combining regulatory change, incentives and opportunities for learning and innovation, is urgently required to meet the challenges that we face.

New farm policies can provide incentives and regulatory standards to encourage innovation and ambition in more effective and efficient nutrient management techniques and systems, stimulating market players. Such innovation can lead to improvements in affordable and reliable tests and measurement, in technological solutions to reduce nutrient losses to the environment, and in plant nutrient materials.

Recommendation 5

To deliver a strategy, a national Nutrient Management Action Plan is needed which is clear and coherent, based on evidence, and sets out the particular responsibilities of each main group of actors and institutions in working to achieve these goals.

There are examples from other countries and in other topic areas of effective policies where government, sector organisations and other key stakeholders work in close partnership to develop a strategy and action plan, overseeing how evidence is gathered and analysed and agreeing how best to organise the response: we commend this approach.

A coherent policy delivery model is needed that is clear, based on evidence, and sets out the responsibilities of each main group of actors and institutions in achieving change and pursuing targets, over time. There are examples from other countries and in other topic areas of effective policy where government, agri-business and farmers organisations and other key stakeholders work in close partnership to develop a strategy and action plan, overseeing how evidence is gathered and analysed and agreeing how best to organise the response: we commend this approach.

Recommendation 6

Among the critical resources that we have considered, soil is one in which the scientific knowledge base is still developing. Defra should consider setting new targets for specific services from the soil, as soil functioning is critical to reducing nutrient emissions to air and water, maintaining biodiversity above and below ground, and supporting plant production.

Whilst 'soil health' does not have a singular definition, there is an array of specific physical, chemical, and biological soil health indicators that can be used. Modelling tools are also increasingly available. Key indices could be promoted, to help farmers assess the condition of their soils and identify potential restoration interventions.

Recommendation 7

Defra should more strongly promote nutrient management planning as central to achieving greater nutrient use efficiency, and thereby reducing adverse environmental outcomes. There is scope for reducing nutrient input without a significant loss of yield, through improved nutrient management, to reduce the waste of valuable nutrient resources from farming systems.

While nutrient inputs are essential for food production, over-use of both organic and inorganic fertilisers has serious environmental consequences. The promotion of good nutrient management planning is central to achieving greater nutrient use efficiency, and thereby positive environmental and productive outcomes. More practical nutrient management plans (NMPs) could be promoted under new government incentive schemes, or incorporated into potential future soil regulation, enforcement mechanisms and other support that will replace cross-compliance requirements, set to be phased out in 2024. Currently, where plans do exist they are not always used to full effect, or not based on crop requirements and up-to-date soil testing. Access to soil testing labs for standardised, quick and low-cost analysis is important, as it helps farmers calculate their inputs more accurately to match soil and crop need. Further innovation and investment are needed in low-cost techniques to assess the nutrient content of both organic materials and soils. These could be used to inform a payment-by-results approach for soils, within the UK's new farming support policies.

Recommendation 8

Nutrient management policy should be flexible and adaptive to reflect the diversity of environmental conditions as well as farming systems throughout the UK.

The challenges of nutrient management vary with farm type, sector, soils and environmental character. At farm level, specific ecological, soil and agronomic conditions mean that even neighbouring farmers may need different strategies to manage their soils, the utilisation of nutrients and the passage of water through them. On a field level, variation in soil characteristics and nutrient supply means that uniform farming practices will rarely be appropriate. Soil is a complex system that requires different management depending on the services that it provides. Farmers should be equipped with detailed knowledge of their own soils and need to be supported as they develop specific plans and tactics to suit their land and their business approach.

Recommendation 9

Defra should establish a campaign in partnership with sector organisations to raise awareness of the substantial financial value of organic materials and nutrients currently wasted, which can be reduced through improved planning and management. To better manage nutrient loadings, farmers should be encouraged by standards, advice and financial incentives to prioritise optimal use of organic materials such as manures and reduce excess inorganic fertiliser inputs.

Recommendation 10

Nutrient budgeting should be established as a basic standard for all farmers and land managers, and expectations applied appropriately to farms with different levels of nutrient loading.

Farms producing livestock excreta should be subject to a regulatory approach which requires the effective utilisation of these nutrients in crop (including grass) fertilisation, maximising their capacity in replacing inorganic fertilisers. If such utilisation cannot be fully achieved without over-application on the farm itself, alternative options are needed to efficiently use these nutrients (such as export to other farms or to anaerobic digestion plants for energy generation). Farmers should assess the sustainability of businesses generating an excess of manures, and be supported and given time to make structural adjustments to ensure they can manage any excess nutrients responsibly. NVZ Action Plans already define maximum stocking rates to help address excess loadings in the most vulnerable areas, but these risks apply more generally across the sector and a more ambitious and comprehensive response is needed to deliver anticipated environmental outcomes.

Recommendation 11

Notwithstanding the importance and urgency of achieving more ambitious nutrient management goals, we uphold the principle that policies should not unduly penalise farming and food production. Responsible farms must be enabled to stay in business, provided that they meet an acceptable level of good agricultural practice, while adapting their approaches, innovating, and mitigating against environmental harm.

Costs to farmers for new infrastructure and switching to more environmentally friendly practices remain a significant barrier to enhanced environmental protection. Where improved infrastructure provides a mainly public rather than private benefit, there is a case for public support to such investment to be funded at higher than the normal 40% or 50% rates, or for related investment loans to be underwritten by public bodies, rather than farmers themselves. Some increased cost to farmers may also be translated into higher prices, which would need to be passed along the supply chain and actively supported by the retail sector. In general, market prices along the supply chain should more accurately reflect the true costs of input use and management, collectively referred to as environmental damage costs.

Recommendation 12

A more joined-up and long-term, consistent policy approach to improving nutrient management needs to be communicated in a clear and accessible way.

The specific interpretation of new regulations needs to be agreed between key actors including farming organisations, prior to roll-out. Recent regulatory changes (such as Farming Rules for Water) have raised governance and system challenges which require further development. There is a key role for Defra in facilitating coordination and ensuring consistency between actors and experts in policy, regulation, practice and science. Clear, unambiguous language, illustrated by demonstration and practical follow-through, are needed to minimise differences in the interpretation of guidance and regulations. Policy should have a strong focus on recognising, supporting and extending farmers', land managers' and relevant supply chain actors' knowledge and skills, to achieve change. The effectiveness of any intervention, regulatory or voluntary, depends on the support package offered at launch and throughout roll-out. Farmers must understand the implications of nutrient management and be able to optimise their nutrient usage while minimising environmental damage. Where there is a need for farmers to change practices or systems, they need to be presented with locally relevant information explaining the specific environmental impacts that must be addressed. Farmer-farmer interactions can be effective in sharing knowledge, also drawing upon 'expert' science input and appropriate facilitation, to generate optimal solutions. Co-generation of knowledge will be key in securing more fundamental change: farmers need to be part of a collective journey with scientists, policy makers, food sector players and other key partners, to address these challenges. They are a vital part of the solution.

Recommendation 13

Key guidance documentation and standards, notably the Nutrient Management Guide (RB209) published by the AHDB, must be regularly updated to ensure they are based on the full breadth of evidence emerging from practitioners, research and policy makers.

Governance of RB209 should ensure a balanced representation of all sources of evidence contributing to revisions of this guidance, and there may be a key role for Defra to play in ensuring this. There is also need for up-to-date computer-based DSTs to support nutrient management and other ecosystem service delivery. Thus, it will be essential to update existing FARMSCOPER, PLANET and MANNER-NPK nutrient management DSTs to ensure they reflect current guidance in the AHDB's Nutrient Management Guide RB209. Making these updates available to commercial software companies would ensure consistency in guidance across the industry. Further, it is essential that any DSTs explicitly referred to in official guidance or advice should be recognised as industry standards, and should give clear and consistent information on nutrient management, holistically incorporating all areas of nutrient pollution. DSTs can also enable data-sharing and benchmarking, to allow farmers to learn from their peers, and develop knowledge and data on which to continue building scientific analysis, improved practice and better policy. For example, a growing range of net zero calculators exists; these can vary significantly in their methodologies, and the reasons for any variations and their consequences should be made transparent to the user.

Recommendation 14

> A clear commitment must be given by government to ensuring that all farmers have access to high-quality, evidence-based and impartial advice, and support to help implement this advice, to reduce nutrient pollution from agriculture. A code of conduct and accreditation scheme such as FACTS or BASIS could be strengthened and widened, to help guarantee the quality, consistency and professionalism of advice from different providers

Nutrient management advice is currently delivered by a variety of providers, including public-funded permanent staff in priority areas, public-contracted providers for specific initiatives, commercial agronomists who may be independent or affiliated with input supply companies and non-profit advisers supported by a subscribing membership. Differing perspectives and expertise can lead to differing advice. Good farm advice requires a breadth of expertise, including a practical grasp of agricultural production methods and commercial aspects, and an in-depth and up-to-date understanding of the environmental impacts (on net zero, soil health, air and water quality) of the full spectrum of nutrient management practices on different farm types. Both incentives and regulatory policies could be designed to strongly encourage every farm to be supported by an advisor or advisory network, which farmers would be free to select from an accredited list. Models of agricultural extension services in other countries could be considered as a source of new ideas for how to strengthen and enhance UK advisory provision, affordability, and access, across the full spectrum of agriculture and land management.

Recommendation 15

> The government has a vital role to play in strengthening the evidence base for future policy development and ensuring that standards and advice promote the public interest in effective nutrient management on farms. It must explicitly acknowledge this key role and the responsibilities that it brings.

Investing proactively in science and technology and pursuing new joint private-public sector partnerships will be essential to fund innovation, applied research, knowledge transfer, and demonstration opportunities. The government should ensure accessibility to the full range of expertise including social science, practitioner, and extension-oriented knowledge.

References

Baveye, P., 2021. Soil health at a crossroad. Soil Use and Management, 37 (2), pp. 215-219.

Bealey W.J., Dore, A.J., Dragosits U., Reis S., Reay DS. and Sutton M.A., 2016. The potential for tree planting strategies to reduce local and regional ecosystem impacts of agricultural NH_3 emissions. Journal of Environmental Management, 165, pp. 106-116.

Bhogal, A., Anthony S., and Gooday R. 2021. Impact Assessment -Farming Rules for Water. Research Review No. 91140078, AHDB.

Bhogal., A Nicholson, F.A., Rollett, A., Taylor, M.J., Litterick, A., Whittingham, M.J. and Williams, J.R., 2018. Improvements in the Quality of Agricultural Soils Following Organic Material Additions Depend on Both the Quantity and Quality of the Materials Applied. Frontiers in Sustainable Food Systems, 2 (9), pp. 1-13.

Bijmans, M.F.M., Buisman, C.J.N., Meulepas, R.J.W. and Lens, P.N.L., 2011. Sulphate Reduction for Inorganic Waste and Process Water Treatment. In: Comprehensive Biotechnology (second edition). Elsevier. Ch.6.34.

Blackstock, K.L., Ingram, J., Burton, R., Brown, K.M. and Slee, B., 2010. Understanding and influencing behaviour change by farmers to improve water quality. Science of The Total Environment, 408(23), pp. 5631–5638.

Brown, P., Broomfield, M., Cardenas, L., Choudrie, S., Jones, L., Karagianni, E., Passant, N., Thistlethwaite, G., Thomson, A., Turtle, L., Wakeling, D., Bradley, S., Buys, G., Clilverd, H., Gilhespy, S., Glendining, M., Gluckman, R., Hampshire, K., Henshall, P., Hobson, M., Kilroy, E., Malcolm, H., Manning, A., Matthews, R., May, K., Milne, A., Misra, A., Misselbrook, T., Murrells, T. and Pang, Y., 2019. UK Greenhouse Gas Inventory, 1990 to 2017: Annual Report for submission under the Framework Convention on Climate Change. Didcot: Ricardo-AEA.

Brownlie, W.J., Sutton, M.A., Heal, K.V., Reay, D.S. and Spears, B.M., 2022. Our Phosphorus Future. Edinburgh: UK Centre for Ecology and Hydrology.

Business Wales, 2021. Available at: https://businesswales.gov.wales/farmingconnect/business/benchmarking/measure-manage.

Butterbach-Bahl, K., Nemtiz, E., Zaehle, S., Billen, G., Boeckx, P., Erisman, J.W., Garnier, J., Upstill-Goddard, R., Kreuzer, M., Oenema, O., Reis, S., Schaap, M., Simpson, D., de Vries, W., Winiwarter, W. and Sutton, M.A., 2011. Nitrogen as a threat to the European greenhouse balance. In: M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, H. van Grinsven, B. Grizzetti, eds. 2011. The European Nitrogen Assessment. Cambridge: Cambridge University Press. Ch.19.

Cardenas L.M., Bhogal A., Chadwick D.R., McGeough K., Misselbrook T., Rees R.M., Thorman R.E., Watson C.J., Williams J.R., Smith K.A. and Calvet S., 2019. Nitrogen use efficiency and nitrous oxide emissions from five UK fertilised grasslands, Science of The Total Environment, 661, pp. 696-710.

Chambers, B.J., Smith, K.A. and Pain, B.F., 2000. Strategies to encourage better use of nitrogen in animal manures. Soil Use and Management, 16, pp. 157-161

Chivers, C-A., Attorp, A., and Caffyn, A., In press. How and why does agricultural diffuse pollution persist in UK and Irish rivers? An examination of environmental governance and power. [Under review: Journal of Environmental Management].

Climate Change Committee, 2020. The Sixth Carbon Budget, The UK's path to Net Zero. Available at: https://www.theccc.org.uk/publication/sixth-carbon-budget/

Collins, A. L., Zhang, Y., Winter, M., Inman, A., Jones, J. I., Johnes, P. J., Cleasby, W., Vrain, E., Lovett, A. and Noble, L., 2016. Tackling agricultural diffuse pollution: what might uptake of farmer-preferred measures deliver for emissions to water and air? Science of the Total Environment. 547, pp. 269-281.

Cordell, D., Benton, T., Withers, P., Johnes, P. J., Neset, T. and Spears, B. (2022) Transforming food systems: implications for P. Chapter 3 in Brownlie, W.J., Sutton, M.S., Heal, K.V., Reay, D.S., Spears, B.M. (Eds.), Our P Future, United Nations Environment Programme and UK Centre for Ecology and Hydrology, Edinburgh. doi: 10.13140/RG.2.2.10598.91201.

Cowan N., Carnell E., Skiba U., Dragosits U., Drewer J. and Levy P., 2020. Nitrous oxide emission factors of mineral fertilisers in the UK and Ireland: A Bayesian analysis of 20 years of experimental data, Environment International, 133, pp. 105-366.

Dalgaard, T., Hansen, B., Hasler, B., Hertel, O., Hutchings, N.J., Jacobsen, B.H., Stoumann Jensen, L., Kronvang, B., Olesen, J.E., Schjørring, J.K., Sillebak Kristensen, I., Graversgaard, M., Termansen, M. and Vejre, H., 2014. Policies for agricultural nitrogen management-trends, challenges and prospects for improved efficiency in Denmark. Environmental Research Letters, 9 (11).

Darwin, E., Johnson, J. and Bensley, T., 1800. Phytologia, or, The philosophy of agriculture and gardening: with the theory of draining morasses, and with an improved construction of the drill plough. London.

DECC and Defra, 2011. Anaerobic Digestion Strategy and Action Plan. [pdf] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69400/anaerobic-digestion-strat-action-plan.pdf

Defra 2018c. Rules for farmers and land managers to prevent water pollution. Available at: https://www.gov.uk/guidance/rules-for-farmers-and-land-managers-to-prevent-water-pollution

Defra 2020a. The Path to Sustainable Farming: An Agricultural Transition Plan 2021 to 2024. [online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/406928/pb14019-anaerobic-digestion-annual-report-2013-14.pdf

Defra, 2015. Anaerobic Digestion Strategy and Action Plan Annual Report 2014. [pdf] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/406928/pb14019-anaerobic-digestion-annual-report-2013-14.pdf

Defra, 2018a. Code of Good Agricultural Practice for Reducing Ammonia Emissions. [pdf] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/729646/code-good-agricultural-practice-ammonia.pdf

Defra, 2018b. A Green Future: Our 25 Year Plan to Improve the Environment. [pdf] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf

Defra, 2019. Clean Air Strategy 2019. [pdf] Defra. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770715/clean-air-strategy-2019.pdf

Defra 2020. Consistent municipal recycling collections in England, Impact Assessment. Available at: https://consult.defra.gov.uk/waste-and-recycling/consistency-in-household-and-business-recycling/supporting_documents/Consistency%20in%20recycling%20impact%20assessment.pdf

Defra, 2022a. ENV01 – Emissions of air pollutants. [online]. Available at: https://www.gov.uk/government/statistical-data-sets/env01-emissions-of-air-pollutants

Defra, 2022b. Consultation on environmental targets. [online]. Available at: https://consult.defra.gov.uk/natural-environment-policy/consultation-on-environmental-targets/supporting_documents/Environment%20Targets%20Public%20Consultation.pdf

Dragosits, U., Carnell, E.J., Tomlinson, S.J., Misselbrook, T.H., Rowe, E.C., Mitchell, Z., Thomas, I.N., Dore, A.J., Levy, P., Zwagerman, T., Jones, L., Dore, C., Hampshire, K., Raoult, J., German, R., Pridmore, A., Williamson, T., Marner J, B., Hodgins, L., Laxen, D., Wilkins, K., Stevens, C., Zappala, S., Field, C. and Caporn, S.J.M., 2020. Nitrogen Futures. Peterborough: JNCC. JNCC Report no. 665.

Durand, P., Breur, L., Johnes, P. J. (Lead Authors), with van Grinsven, H., Butturini, A., Billen, G., Garnier, J., Maberley, S., Carvalho, L., Reay, D. and Curtis, C., 2011. Nitrogen processes in aquatic ecosystems. In: M. A. Sutton, C. M. Howard, J. W.

Erisman, G. Billen, A. Bleeker, P. Grennfelt, H. van Grinsven, B. Grizzetti, eds. 2011. The European Nitrogen Assessment. Cambridge: Cambridge University Press. Ch.7.

ELM, 2021. Environmental Land Management and Public Money for Public Goods. (PDF) ELM. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/955920/ELM-evidencepack-28jan21.pdf

Entrade, 2022. Entrade. [online] Available at: EnTrade.

Environment Act 2021. [online] Available at: https://www.legislation.gov.uk/ukpga/2021/30/contents/enacted

Environment Agency, 2019. Catchment Sensitive Farming – Evaluation Report – Water Quality Phases 1 to 4 (2006 to 2018). (PDF) Natural England. Available at: http://publications.naturalengland.org.uk/publication/4538826523672576

Fawzy, S., Osman, A.I., Doran, J., and Rooney, D.W., 2020. Strategies for mitigation of climate change: a review. Environmental Chemistry Letter, 18, pp. 2069–2094.

Freeman, D., Wiltshire, J., and Jenkins, B., 2020. Evidence review of the efficacy of nitrification and urease inhibitors. ClimateXChange Publications. Available at: https://era.ed.ac.uk/handle/1842/37148

Geissdoerfer, M., Savaget, P., Bocken, N.M.P. and Hultink, E.J., 2017. The Circular Economy – A new sustainability paradigm? Journal of Cleaner Production, 143, pp.757–768.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. and Tempio, G., 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Rome: Food and Agriculture Organization of the United Nations (FAO). Available at: https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1235389/

Glibert P.M., Harrison J., Heil C., and Seitzinger S., 2006. Escalating worldwide use of urea – a global change contributing to coastal eutrophication. Biogeochemistry, 77, pp. 441-463.

Goulding, K.W.T., Poulton, P.R., Webster, C.P. and Howe, M.T., 2000. Nitrate leaching from the Broadbalk Wheat Experiment, Rothamsted, UK, as influenced by fertilizer and manure inputs and the weather. Soil Use and Management, 16(4), pp. 244–250.

Graves A.R., Morris J., Deeks L. K., Rickson R. J., Kibblewhite M. G., Harris J. A., Farewell T. S., Truckle I., 2015. The total costs of soil degradation in England and Wales. Ecological Economics, 119, pp. 399-413.

Greene, S., Johnes, P. J., Reaney, S., Bloomfield, J. P., Freer, J. E., Macleod, C. J. M. and Odoni, N., 2015. A geospatial framework to support integrated biogeochemical modelling in the UK. Environmental Monitoring and Software, 68, pp. 219-232.

Ingram, J., Dwyer J., Gaskell, P., Mills, J. and de Wolf, P., 2018. Reconceptualising translation in agricultural innovation: A co-translation approach to bring research knowledge and practice closer together. Journal of Land Use Policy, 70, pp. 38-51.

Inman, A., Winter, M., Wheeler, R., Vrain, E., Lovett, A., Collins, A., Jones, I., Johnes, P. and Cleasby, W., 2018. An exploration of individual, social and material factors influencing water pollution mitigation behaviours within the farming community. Land Use Policy, 70, pp. 16–26.

Istvánovics V., 2009. Eutrophication of Lakes and Reservoirs. In: G. E. Likens, ed. 2009. Encyclopedia of Inland Waters. Oxford: Elsevier. pp. 157-165.

James, C., Fisher, J., Russell, V., Collings, S., and Moss, B., 2005. Nitrate availability and hydrophyte species richness in shallow lakes. Freshwater Biology, 50, pp. 1049–1063.

Johnes, P. J., Heathwaite, A. L., Spears, B. M., Brownlie, W. J., Elser, J., Haygarth, P. M., Macintosh, K. A., Withers, P. J. (2022) P and water quality. Chapter 5 in Brownlie, W.J., Sutton, M.S., Heal, K.V., Reay, D.S., Spears, B.M. (Eds.), Our P Future. United Nations Environment Programme and UK Centre for Ecology and Hydrology, Edinburgh. doi: 10.13140/RG.2.2.14950.50246.

Jones, G., Moran, J. and Robins, M., 2019. European Innovation Partnerships - Agriculture (EIP-AGRI) in Ireland 2014-20 – lessons and recommendations for policy post-2020. 10.13140/RG.2.2.28683.62245.

Kane, D.A., Bradford, M.A., Fuller, E., Oldfield, E.E. and Wood, S.A., 2021. Soil organic matter protects US maize yields and lowers crop insurance payouts under drought. Environmental Research Letters, 16(4), p.044018.

Knapp, S. and van der Heijden, M.G.A., 2018. A global meta-analysis of yield stability in organic and conservation agriculture. Nature Communications, 9(1).

Kronvang, B., Andersen, H.E., Børgesen, C., Dalgaard, T., Larsen, S.E., Bøgestrand, J. and Blicher-Mathiasen, G., 2008. Effects of policy measures implemented in Denmark on nitrogen pollution of the aquatic environment. Environmental Science and Policy, 11(2), pp. 144–152.

Lamb, W. F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J.G.J., Wiedenhofer, D., Giulio Mattioli, G., Khourdajie, and A. A., House, J., 2021. A review of trends and drivers of greenhouse gas emissions. Environmental Research Letters, 16.

LENs, 2022. Landscape Enterprise Network. [online] Available at: https://landscapeenterprisenetworks.com

Lloyd, C, Johnes, P, Freer, J, Carswell, A, Jones, JI, Stirling, MW, Hodgkinson, RA, Richmond, C and Collins, AL 2019. 'Determining the sources of nutrient flux to water in headwater catchments: Examining the speciation balance to inform the targeting of mitigation measures', Science of The Total Environment, vol. 648, pp. 1179-1200. https://doi.org/10.1016/j.scitotenv.2018.08.190

Mackay, E.B., Feuchtayr, H., De Ville, M.M., Thackeray, S.J., Callaghan, N., Marshall, M., Rhodes, G., Yates, C.A., Johnes, P.J., and Maberly, S.C., 2020. Dissolved organic nutrient uptake by riverine phytoplankton varies along a gradient of nutrient enrichment. Science of The Total Environment, 722.

Manisalidis, I., Stavropoulou, E., Stavropoulos, A. and Bezirtzoglou, E., 2020. Environmental and Health Impacts of Air Pollution: A Review. Frontiers in Public Health, 8(14).

Martínez-Dalmau, J., Berbel, J. and Ordóñez-Fernández, R., 2021. Nitrogen Fertilization. A Review of the Risks Associated with the Inefficiency of Its Use and Policy Responses. Sustainability,13(10), p.5625.

Masso C., Zhang, F., Adhya, T., Blackwell, M., Macintosh, K., Johnes, P. J., Haygarth, P. M., Withers, P., Feng, G., Li, H., Zhang, C., Wu. J., Wu, J., Shen, J., Stutter, M., Cheng, L. and Brownlie, W., 2022. Opportunities for better phosphorus use in agriculture. In: W.J. Brownlie, M.S. Sutton, K.V. Heal, D.S. Reay, and B.M. Spears, eds. 2022. Our Phosphorous Future. Edinburgh: United Nations Environment Programme and UK Centre for Ecology and Hydrology. Ch.4.

Mills, G., Vieno, M., Sharps, K. Hall, J. Harmens, H., and Hayes, F., 2017. Scoping Study for NECD Reporting for Effects of Ozone on Vegetation in the UK under contract AQ0833 (International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops 2014-2017) , Report available at: http://sciencesearch.defra.gov.uk/Document.aspx?Document=14177_NECDreportICPVegetationWP7_AQ0833_submitted.pdf

Mills, J, Gibbon, D, Ingram, J, Reed, M, Short, C J and Dwyer, J C,. 2011. Organising Collective Action for Effective Environmental Management and Social Learning in Wales. Journal of Agricultural Education and Extension, 17 (1). pp. 69-83. doi:10.1080/1389224X.2011.536356

Misselbrook, TH. and Gilhespy, SL., 2022b. Inventory of Ammonia Emissions from UK Agriculture 2020. [document] Devon: Rothamsted Research, Defra Contract SCF0107.– 2017. Available at: https://uk-air.defra.gov.uk/assets/documents/reports/cat07/2207140931_UK_Agriculture_Ammonia_Emission_Report_1990-2020_final.pdf

Misselbrook, TH., 2022a. Email conversation discussing the impact of BAT techniques on overall NH_3 emissions in livestock housing. (3 August 2022).

Morecroft, M.D., Bealey, C.E., Beaumont, D.A., Benham, S., Brooks, D.R., Burt, T.P., Critchley, C.N.R., Dick, J., Littlewood, N.A., Monteith, D.T., Scott, W.A., Smith, R.I., Walmsley, C. and Watson, H., 2009. The UK Environmental Change Network: Emerging trends in the composition of plant and animal communities and the physical environment. Biological Conservation, 142(12), pp. 2814–2832.

Moss, B., Johnes, P. J. and Phillips, G. L. 1996. The monitoring and classification of standing waters in temperate regions - a discussion and proposal based on a worked scheme for British waters, Biological Reviews, 71, 2, pp. 310-339.

National atmospheric Emission Inventory, 2021. United Nations Framework Convention on Climate Change (UNFCCC). [online] Available at: https://naei.beis.gov.uk/about/why-we-estimate?view=unfccc.

Henry Dimbleby's independent review on a National Food Strategy, 2021. [online] Available at: https://www.nationalfoodstrategy.org/the-report/

National Statistics, 2021a. British survey of fertiliser practice 2020. [online] Available at: https://www.gov.uk/government/statistics/british-survey-of-fertiliser-practice-2020

National Statistics, 2021b. Agri-climate report 2021. [online] Available at: https://www.gov.uk/government/statistics/agri-climate-report-2021/agri-climate-report-2021.

National Statistics, 2022. 2020 UK Greenhouse Gas Emissions, Final Figures. (PDF) Department for Business, Energy and Industrial Strategy. Available at: https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2020

Natural England, 2015. Atmospheric nitrogen theme plan, Developing a strategic approach for England's Natura 2000 Sites. [pdf] Natural England. Available at: http://publications.naturalengland.org.uk/publication/6140185886588928

NE, EA and Defra, 2011. Catchment Sensitive Farming Phase 1 and 2 Evaluation. Natural England, 2013. Available at: http://publications.naturalengland.org.uk/publication/5329340644458496?category=45002 Accessed 3/11/22

Ockenden, M.C., Hollaway, M.J., Beven, K.J. et al. 2017. Major agricultural changes required to mitigate phosphorous losses under climate change. Nature Communication 8, 161.

Omara, P., Aula, L., Oyebiyi, F., Raun, W.R., 2019. World Cereal Nitrogen Use Efficiency Trends: Review and Current Knowledge. Journal of Agrosystems, Geosciences and Environment. 2(1), pp. 1-8.

Otten, W., 2021. Advances in measuring soil health. London: Burleigh Dodds Science Publishing.

Pardo, G., Moral, R., Aguilera, E. and del Prado, A., 2014. Gaseous emissions from management of solid waste: a systematic review. Global Change Biology, 21(3), pp.1313–1327.

Poikane, S., Kelly, M.G., Herrero, F.S., Pitt J-A., Jarvie, H.O., Claussen, U., Leujak, W., Solheim, A.L., Teixeira, H. and Phillips, G., 2019. Nutrient criteria for surface waters under the European Water Framework Directive: Current state-of-the-art, challenges and future outlook. Science of The Total Environment, 695,133888.

Quinton, J.N., Öttl, L.K. and Fiener, P., 2022. Tillage exacerbates the vulnerability of cereal crops to drought. Nature Food, 3, pp. 372-479.

Ragn-Sells, 2022. What we do. [online] Available at: https://www.ragnsells.com/what-we-do/inspired/project-n/

Ravishankara, A.R., Daniel, J.S. and Portmann, R.W., 2009. Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century. Science, 326(5949), pp.123–125.

Raza, S., Zamanian, K., Ullah, S., Kuzyakov, Y., Virto, I. and Zhou, J., 2021. Inorganic carbon losses by soil acidification jeopardize global efforts on carbon sequestration and climate change mitigation. Journal of Cleaner Production, 315.

Rogelj, J., Schaeffer, M., Meinshausen, M., Knutti, R., Alcamo, J., Riahi, K. and Hare, W., 2015. Zero-emission targets as long-term global goals for climate protection. Environmental Research Letters. 10.

Rosemarin, A., Macura, B., Carolus, J., Barquet, K., Ek, F., Järnberg, L., Lorick, D., Johannesdottir, S., Pedersen, S., Koskiaho, J., Haddaway, N. and Okruszko, T., 2020. Circular nutrient solutions for agriculture and wastewater – a review of technologies and practices. Current Opinion in Environmental Sustainability, 45, pp. 78-91,

Sgouridis, F. and Ullah, S., 2015. Relative Magnitude and Controls of in Situ N_2 and N_2O Fluxes due to Denitrification in Natural and Seminatural Terrestrial Ecosystems Using ^{15}N Tracers. Environmental Science and Technology, 49(24), pp. 14110–14119.

Smith, O.M., Cohen, A.L., Rieser, C.J., Davis, A.G., Taylor, J.M., Adesanya, A.W., Jones, M.S., Meier, A.R., Reganold, J.P., Orpet, R.J., Northfield, T.D. and Crowder, D.W., 2019. Organic Farming Provides Reliable Environmental Benefits but Increases Variability in Crop Yields: A Global Meta-Analysis. Frontiers in Sustainable Food Systems, 3.

Stahel, W., 2016. The circular economy. Nature, 531, pp 435-438.

Statista, 2022. Deaths from particle pollution (PM2.5) in the United Kingdom 2011-2019. [online] Available at: https://www.statista.com/statistics/789921/particle-pollution-deaths-united-kingdom-uk/

Storkey, J., Macdonald, A.J., Poulton, P.R., Scott, T., Köhler, I.H., Schnyder, H., Goulding, K.W.T. and Crawley, M.J., 2015. Grassland biodiversity bounces back from long-term nitrogen addition. Nature, 528(7582), pp. 401–404.

Sutherland, Lee-Ann, Mills, Jane , Ingram, Julie , Burton, Rob J F, Dwyer, Janet C. and Blackstock, Kirsty, 2013. Considering the source: Commercialisation and trust in agri-environmental information and advisory services in England. Journal of Environmental Management, 118. pp. 96-105. doi:10.1016/j.jenvman.2012.12.020

Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizzetti, B., de Vries, W., van Grinsven, H.J.M., Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E.A., Datta, A., Diaz, R., Erisman, J.W., Liu, X.J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R.W., Sims, T., Westhoek, H. and Zhang, F.S., 2013. Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management. Edinburgh: Centre for Ecology and Hydrology on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative.

Sylvester-Bradley, R. and Kindred, D., 2021. Review of how best to respond to expensive fertiliser nitrogen for use in 2022 (part one). AHDB Research Review, 97.

Taft, H., Chadwick, D., Styles, D., Kipling, R., Newbold, J. and Moorby, J., 2018. A review of GHG calculators for use in the Welsh agricultural sector. A Climate Smart Agriculture (Wales) Report. Aberystwyth and Bangor Universities, Wales.

The Conservation of Habitats and Species Regulations 2017. 2017 SI 2017/1012. London: Legislation.gov.uk

The Royal Society, 2021. The effects of net-zero policies and climate change on air quality. [Online] Available at: https://royalsociety.org/-/media/policy/projects/air-quality/air-quality-and-climate-change-report.pdf

Tipping, E., Davies, J.A., Henrys, P.A., Jarvis, S.G., Rowe, E.C., Smart, S.M., Le Duc, M.G., Marrs, R.H. and Pakeman, R.J., 2019. Measured estimates of semi-natural terrestrial NPP in Great Britain: comparison with modelled values, and dependence on atmospheric nitrogen deposition. Biogeochemistry, 144(2), pp. 215-227.

Tipping, E., Davies, J.A., Henrys, P.A., Kirk, G.J., Lilly, A., Dragosits, U., Carnell, E.J., Dore, A.J., Sutton, M.A. and Tomlinson, S.J., 2017. Long-term increases in soil carbon due to ecosystem fertilization by atmospheric nitrogen deposition demonstrated by regional-scale modelling and observations. Scientific reports, 7(1), pp. 1-11.

UNECE, 2021. Report of the Task Force on Reactive Nitrogen. [pdf] UNECE. Available at: https://unece.org/sites/default/files/2021-03/ECE_EB.AIR_WG.5_2021_2-2102622E.pdf

United Nations Economic Commission for Europe (UNECE), 2021. Guidance Document on Integrated Sustainable Nitrogen Management. [pdf] Economic

Commission for Europe. Available at: https://unece.org/sites/default/files/2021-04/Advance%20version_ECE_EB.AIR_149.pdf

United Nations Framework Convention on Climate Change (UNFCCC), 2021. The Paris Agreement. [online] Available at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Viguier, L., Bedoussac, L., Journet, EP., and Justes, E. Correction to: Yield gap analysis extended to marketable grain reveals the profitability of organic lentil-spring wheat intercrops. Agron. Sustain. Dev. 38, 46 (2018). https://doi.org/10.1007/s13593-018-0531-5

Vollenweider, R.A. and Kerekes, J. J. 1982. Background and summary results of the OECD cooperative programme on eutrophication, OECD, Paris.

Weidema, Bo P., Thrane, M., Christensen, P., Schmidt, J. and Lokke, S., 2008. Carbon Footprint. A Catalyst for Life Cycle Assessment? Journal of Industrial Ecology 12(1), pp. 3-6.

Whitmore, A., Watts, C., Stroud, J., Sizmur, T., Ebrahim, SM., Pawlett, M., Harris, J., Ritz, K., Wallace, P., White, E., Stobart, R., McKenzie, B. and Thallon, G., 2017. Improvement of soil structure and crop yield by adding organic matter to soil (AHDB Project Report No.576). Stoneleigh Agriculture and Horticulture Development Board.

Wood S. and Cowie A., 2004. A review of greenhouse gas emission factors for fertiliser production. Paris, France: IEA Bioenergy.

Woods, J., Williams, A., Hughes, J.K., Black, M. and Murphy, R., 2010. Energy and the food system. Philosophical Transactions of the Royal Society London B. 365(1554). pp. 2991–3006.

WRAP, 2020a. AD and Composting Industry Market Survey Report 2020. [document] WRAP. Available at: https://wrap.org.uk/sites/default/files/2021-01/AD%20%26%20Composting%20Market%20Survey%20Report.pdf

WRAP, 2020b. WRAP Information Sheet – Review: Technologies to optimise the value of digestate (2020). [online] WRAP. Available at: https://www.r-e-a.net/resources/wrap-review-technologies-to-optimise-the-value-of-digestate/

Wymore, A. S, Johnes, P. J., Bernal, S., Brookshire, E. N. J., Fazekas, H. M., Helton, A. M., Argerich, A., Barnes, R. T., Coble, A. A., Dodds, W. K., Haq, S., Johnson, S. L., Jones, J. B., Kaushal, S. S., Kortelainen, P., Lopez-Lloreda, C., Rodriquez-Cardona, B., Spencer, R. G. M., Sullivan, P. L., Yates, C. A. and McDowell, W. H., 2021. Gradients of anthropogenic nutrient enrichment alter N composition and DOM stoichiometry in freshwater ecosystems. Global Biogeochemical Cycles, 35(8).

Yates, C. A., Johnes, P. J., Owen, A. T., Brailsford, F. L., Glanville, H. C., Evans, C. D., Marshall, M. R., Jones, D. L., Lloyd, C. E. M., Jickells, T. and Evershed, R. P., 2019.

Variation in dissolved organic matter (DOM) stoichiometry in freshwaters: assessing the influence of land cover and soil C:N ratio on DOM composition. Limnology and Oceanography. 64(6), pp. 2328-2340.

Yue, X.-L. and Gao, Q.-X., 2018. Contributions of natural systems and human activity to greenhouse gas emissions. Advances in Climate Change Research, 9(4), pp. 243–252.

Yuille, A., Rothwell, S., Blake, L., Forber, K.J., Marshall, R., Rhodes, R., Waterton, C. and Withers, P.J.A., (2022). UK Government Policy and the Transition to a Circular Nutrient Economy. Sustainability, 14(6), p.3310.

Zhang, Y., Collins, A. L., Jones, J. I., Johnes, P. J., Inman, A. and Freer, J. E., 2017a. The potential benefits of on-farm mitigation scenarios for reducing multiple pollutant loadings in prioritised agri-environment areas across England. Environmental Science and Policy. 73, pp. 100-114.

Zhang, Y., Collins, A.L., Johnes, P. J. and Jones, J.I., 2017b. Projected impacts of increased uptake of source control mitigation measures on agricultural diffuse pollution emissions to water and air across England and Wales. Land Use Policy 62, pp. 185-201.