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Target setting for nitrogen use efficiency in Scotland

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1. Executive summary

1.1. Background

The Scottish Government's Climate Change Plan Update (CCPu) sets out an ambition for the agriculture sector to reduce emissions by 31% from 2019 levels by 2032, and a commitment to "work with the agriculture and science sectors regarding the feasibility and development of a SMART target for reducing Scotland's emissions from nitrogen (N) fertiliser."

The agricultural sector is dependent on N inputs, both organic and inorganic. The inefficient use of these inputs creates N wastage, impacting air and water quality and the climate. The global nature of the issue provides an opportunity for Scottish agriculture to learn from other countries on how to improve Nitrogen Use Efficiency (NUE), i.e. taking action to reduce agricultural N losses while maintaining and supporting the sector in terms of income and yield.

This report explores the potential for setting a NUE target for agriculture in Scotland. It examines N flows found in Scottish agriculture as shown in the Scottish Nitrogen Balance Sheet (SNBS), providing a clear analysis of the opportunities and barriers.

1.2. Key findings

Whilst there is theoretical potential for setting a NUE target for Scotland, there are practical obstacles that policy makers would need to overcome for the target to be implemented.

This research argues sector specific NUE values are not currently feasible due to the calculation set-up in the SNBS and the assumption that production will remain stable, with only inputs decreasing.

- We suggest that the SNBS calculations need refinement to attribute flows of N to the different measures and sectors. In the current version of the SNBS, the NUE calculations do not align directly with what happens in practice because there

  - are overlaps and movements of N flows between the different agricultural sectors.
  - These are not easily viewed in isolation and not necessarily attributed to the correct sector. For example, mitigation measures around manure management will, in practice, be mainly implemented by the livestock sector but will, in the current calculations, be attributed to the arable sector because they are linked to reduced emissions from spreading of organic matter to soils.

1.2.1. Opportunities

- The SNBS would offer an effective data source for setting and monitoring progress towards a single nationwide NUE target that covers all sectors.
- Many mitigation measures with known impacts on reducing N waste and improving N use are already in use in Scotland. Measures with the greatest potential improvement on NUE are
  - nitrification inhibitors
  - improving livestock nutrition, and
  - improving livestock health.
  - **Note** - that the improvement reflects implementing the relevant measure individually and does not consider any combination effects or interactions with other measures.
- The lowering of N-related emissions through reaching a NUE target will positively contribute to other emission reduction targets and the potential for an increase in farm business profitability.

1.2.2. Barriers

- Since a sector specific NUE target is currently not feasible, the remaining option is a single nationwide target.
  - However, the arable, horticultural and livestock sectors would need to implement distinct mitigation measures, start from differing baselines, and will react inconsistently to implemented changes. This is partially due to the current limitations in the SNBS, but also due to the much lower baseline of current NUE values, setting a nationwide NUE target might cause the livestock sector to feel unfairly targeted.
- Some mitigation measures require significant capital expenditure to implement.
- The concept of NUE is complex and clear communication is required to ensure that targets and measures are clearly understandable and achievable to generate support from the farming sector.
- We examined different scenarios to model a potential target. The table below shows an achievable target and one that is more ambitious. The 2045 (Ambitious) scenario is based on transformational change across the sector.

	Potentially achievable NUE estimates (%)				
	2021 (Current)	2030	2040	2045	2045 (Ambitious)
Whole agriculture	27.2	33.7	35.7	38.2	40.9

- No country currently uses a standalone NUE target. Several countries have set N-related targets, some of which include information on NUE. Notably, the Colombo Declaration represents the first time that governments are collaborating on a global N management target on N waste.

1.3. Conclusions and recommendations

While this research identified opportunities for setting a NUE target for Scottish agriculture, more work is needed to fully understand the following elements:

- differential flows for each sector
- make appropriate changes to the SNBS
- ensure that the role of legumes in emissions reduction is fully integrated and
- carefully plan communication to achieve support from the farming sector.

A NUE target is **not currently the most appropriate option for Scotland**. This is partially due to the methodology in the current SNBS.

1.3.1. Recommendations

- Explore the potential for a more granular breakdown, and accurate representation of N flows in the SNBS. This may be difficult but would significantly help both monitoring and setting of a SMART NUE target.
    - Creating a NUE target requires considering several criteria including mitigation measures, current uptake, applicability, expected future uptake, timescales, and sector breakdown. It is important to understand that other agricultural practices may impact N flows, as will changes in the size of agricultural sectors, and achieving these targets in practice will require supporting instruments to encourage the uptake of these measures. This research recommends that:
- N waste be considered as a target instead of a NUE target and that a SMART analysis is carried out to explore a N waste target further. Opportunities for setting a N waste reduction target include:
    - It is an **easier concept to communicate** to the farming community.
    - It values any N as a resource until it is lost as waste, creating options for greater collaboration between the arable, horticulture and livestock sectors. Any potential bias towards a sector will be avoided.
    - A N waste target would achieve reductions in national NUE thereby achieving the same objectives without the current issues around NUE targets.
    - Experience of the United Nations Environment Assembly and the Green Deal's Farm to Fork targets has shown more potential in successfully reducing N

pollution when focusing on reducing **N waste** over NUE targets as a policy option.

- If a decision is made to set a NUE target, the underlying assumptions should first be updated based on latest available evidence, for example using the updated Up to date Farm Census data. would strengthen any underlying assumptions and may directly influence the potential for the mitigation measures, particularly relating to slurry and manure management.
- The **SNBS** be improved by assigning distinct N flows to N waste and N re-use. A SMART target analysis for N waste will be beneficial to set a challenging and realistic target.

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2. Glossary / Abbreviations table

Table 1: Glossary/ abbreviations table

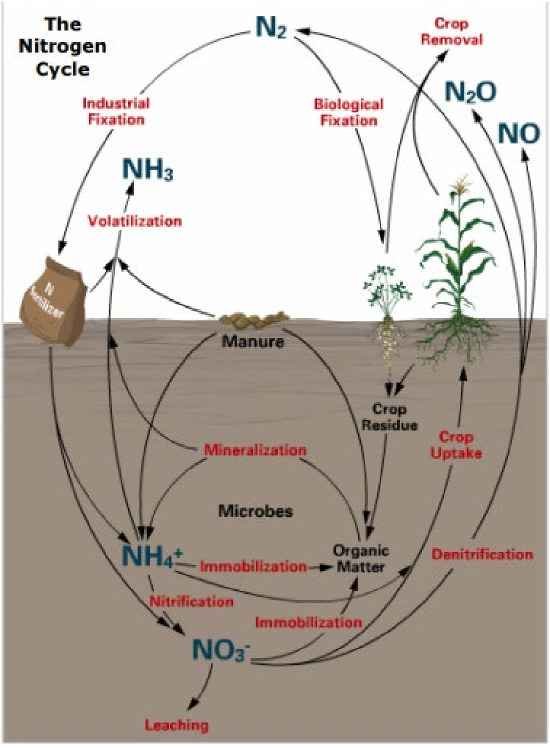
Term/acronym	Definition
CCPu	Climate Change Plan Update
CO_2	Carbon Dioxide
EUNEP	European Union Nitrogen Experts Panel
GHG	Greenhouse gas
INMS	International Nitrogen Management System
kt N / yr	kilo tonnes of nitrogen per year
MtCO2e	Million tonnes of carbon dioxide equivalent
N	Nitrogen
N_2	Di-nitrogen
NH_3	Ammonia
NH_4+	Ammonium
NO_3-	Nitrate
N_2O	Nitrous Oxide
NUE	Nitrogen Use Efficiency
NVZ	Nitrate Vulnerable Zones
PESTLE	Political, Economic, Social, Technical, Legal, Environmental
REA	Rapid Evidence Assessment
SNBS	Scottish Nitrogen Balance Sheet
SWOT	Strengths, Weaknesses, Opportunities, Threats
UNEP	United Nations Environment Program

3. Introduction

3.1. Nitrogen and its relevance to agriculture

Crops require nitrogen (N) to maximise growth. Most crops take up N from the soil in the form of nitrate (NO_3-). NO_3- in soils come from three major sources, the application of organic livestock manures, the application of inorganic N fertilisers and nitrogen fixing plants such as legumes. During harvest and through grazing, N is removed from the system. N can also be lost from soil through NO_3- leaching and through emissions of ammonia (NH_3) and nitrous oxide (N_2O). The N cycle (Figure 1) shows how different forms of N flow through the agricultural system.

Figure 1: The Nitrogen Cycle



An excess of N can both directly and indirectly lead to soil, water and air quality deterioration which is detrimental to human and ecosystem health (e.g., affecting respiratory systems and reducing oxygen in water). According to the IPCC AR5 Synthesis Report, N_2O has a global warming potential (GWP) 273 times that of carbon dioxide (CO_2) over a 100-year timescale. In Scotland N_2O is responsible for a quarter of the agriculture sector's total GHG emissions.

More detail can be found in Appendix A on the process of leaching, the effects of eutrophication and how N_2O and NH_3 are emitted from agricultural sources and in Appendix B on the chemical processes of N conversion.

3.2. Nitrogen Use Efficiency

Nitrogen use efficiency (NUE) describes the ratio between total N input (e.g., fertiliser) and total N output (e.g., harvested product) expressed as a percentage (%). Figure 2 presents a visual example of NUE.

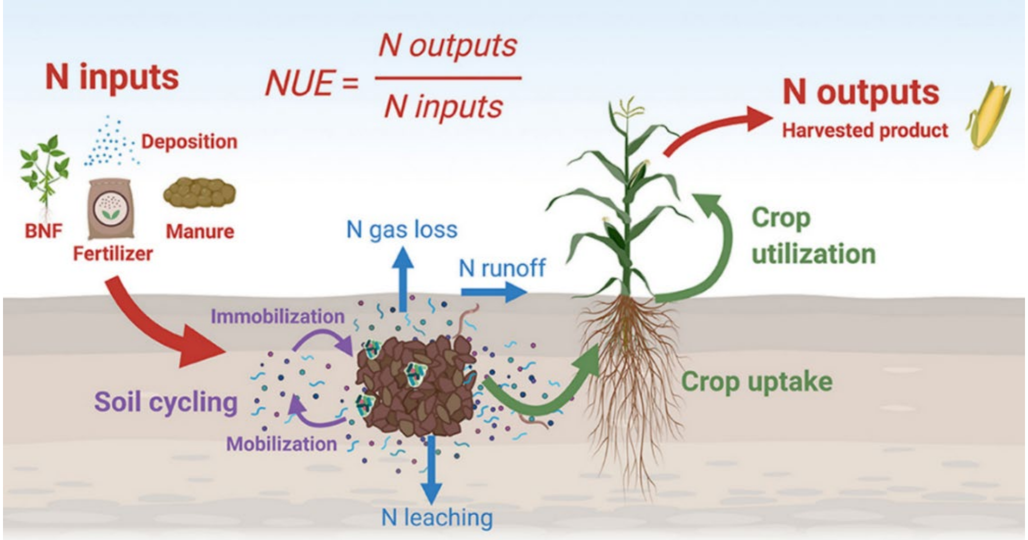


Figure 2. NUE diagram. Source: Udvardi et al., 2021

NUE gives an indication of the efficiency of crop utilisation of N. Generally, the higher the percentage NUE the better as this means less loss of N to air and water and indicates the crop is efficient in the uptake of N. However, pushing the ratio too high (for example over 90% in a cereal crop) can indicate ‘soil nutrient mining’ leaving not enough available N to maintain healthy crop growth and soil ecosystems (Sanchez, 2002). When NUE is too low (less than 50% in cereal crops), a large amount of N is likely being lost to the water and air. An ideal NUE would therefore be between 50% and 90%. NUE efficiency is also greatly impacted by climatic conditions, with changes in microbial activity in drought and frozen soils, along with increased risk of denitrification or leaching when soils are waterlogged.

NUE values are therefore both indicators of resource efficiency and markers for improvement. Key factors influencing NUE include crop type and rotation, soil pH and texture, climate, ammonia, leaching, biological utilisation of N and N management amongst others. As such, an absolute NUE reference value cannot be universally applied and will need to be understood and optimised for specific systems.

4. Nitrogen and NUE targets in other countries

4.1. Introduction

A Rapid Evidence Assessment (REA) seeking evidence relating to the setting and use of nitrogen and NUE targets was undertaken and identified peer-reviewed academic literature as well as government policies and websites. The review also identified grey literature sources such as farming and industry press reports. This search included, but was not limited to, targets for NUE, N emissions and N fertiliser use. The methodology can be found in Appendix C. The review focussed on identifying:

- Relevant scientific research on NUE target setting (4.2)

- Countries with N-related target/s, including types, values and timeframes (4.3)
- Relevance to Scottish agriculture, agricultural sectors and N flows (4.4).

4.2. Research on NUE target setting

This section includes information found through the REA on global NUE trends and relevant scientific research on the possibility of setting a NUE target including the necessary considerations (e.g., differences in farming sectors). 95 sources of literature were reviewed through the REA, 38 of which were from the UK, 32 from European countries and the remaining from other countries from around the world. Search strings used to gather this data can be found in Appendix C.

The NUE trend in the UK shows an increase from 1961 to 2014 (Lassaletta, L et al., 2014) which is likely a response to both regulation and market forces (for example the Nitrates Directive and changes in farm incomes). A full list of country-specific changes (%) in NUE values from 1961 to 2014 can be found in Appendix D. Following on from these observations, the research discussed below highlights the requirements and considerations for setting a NUE target.

Studies such as Quemada et al., 2020 collected farm-level data from 1240 farms across Europe and through statistical analysis, present NUE targets for different agricultural systems (e.g., 23% for a pig farm and 61% for an arable farm) which demonstrates the possibility of setting farm-level NUE targets. However, the study also highlights the importance of how differences in farming sectors will impact target setting.

A study conducted by Antille et al*.,* 2021 states that there is no universal method for the calculation and reporting of NUE across all agricultural sectors. Furthermore, research projects which provide recommendations for NUE targets also suggest that such targets could be dependent on the agricultural system and its management, as well taking the ‘4R nutrient stewardship’ approach (right fertilizer type, right amount, right placement and right time) (Waqas et al., 2023). These approaches are country and region specific, dependent on climate, farmer knowledge, technological advancement and availability.

The EU Nitrogen Experts Panel (EUNEP) (initiated by an industry-based organisation ‘Fertilizers Europe’) recommends a maximum NUE of 90% (Duncombe, 2021), with an ‘ideal range’ of 50% to 90%. This range has been set to reflect that a NUE value below 50% is likely to result in N lost to the environment, while a value above 90% could result in soil N mining. Further detail is given in section 3.2. Whilst it is important to note that values will vary according to context (soil, climate, crop etc), the identification of this ‘ideal range’ by the EUNEP helps us to understand the opportunity and potential for setting a NUE target.

The research has highlighted that whilst it is possible to set NUE targets, there are a number of variables which impact upon *setting* a NUE target. These variables include the differences in farming sectors, differences in farming management, a lack of universal calculation and reporting of NUE, country / region specificity and climate.

4.3. N targets by country - types and policy context

There are currently no standalone country level NUE targets. Several countries, however, have set N targets through various means, some of which include information or actions on NUE. The review of approaches and literature can be summarised as having three main reasons/drivers for introducing N targets, these are all focused on responding to environment and climate impacts of N emissions:

- To lower GHG emissions
- To improve water quality
- To improve air quality

The underlying impact of N-related targets all seek to reduce N waste[1], however, the two primary mechanisms differ in their points of measurement. Some targets are set to reduce N emissions whilst others are set to improved water or air quality. Table 2 gives an overview of existing initiatives across the world and their main N target with relation to agriculture. Many are relatively vague and reflect the difficulty in setting firm policy across regions or countries. No set value was found for the targets in table 2 that do not include a percentage or numeric change. These initiatives or legislation are described in further detail below.

Table 2. Overview of existing initiatives on N targets.

Initiatives and country	N target
Colombo Declaration 2019, United Nations Environment Programme	Halve N waste by 2030
Climate Change Response (Zero Carbon) Amendment Act 2019, New Zealand	Reduce N_2O emissions to net zero by 2050
Nitrates Directive 1991, EU	Reduce NO_3 losses from agricultural sources
National Emissions reduction Commitments Directive 2016, EU	Reduce NH_3 emissions from agriculture
Farm to Fork Strategy 2020, EU	Reduce nutrient losses by at least 50%
Harmony rules, Denmark	Limit N inputs to land from livestock manure
Climate Action Plan 2021, Ireland	Improve NUE
Green transition of the agricultural sector 2021, Denmark	Reduction of N emissions by 10,800 tonnes by 2027
French Climate and Resilience Law 2021, France	Reduction of N_2O emissions by 15% of 2015 levels and NH_3 emissions by 13% of 2005 levels by 2030
National Emissions Ceilings Regulations 2018, UK	Reduction commitments for NH_3 of 16% by 2030 relative to 2005 levels
Wales, UK	Reduction of agricultural GHG emissions by 28% by 2030 compared to 1990

[1] N waste is reactive nitrogen (Nr) that is not used in the nitrogen cycle. Higher N waste reduces NUE.

4.3.1. International action

The UN Environment Program (UNEP) previously considered 'an aspirational goal for a 20% relative improvement in full-chain NUE by 2020' (Sutton et al., 2014). However, Sutton et al., (2021) found that this could lead to an unfair distribution of effort whereby everyone had to increase their NUE by a relative amount. If this was the case a farm currently operating with high efficiency, e.g., 60% NUE, would have to increase by 12% to reach this 20% target. Whereas a farm operating with low efficiency e.g., 10% NUE, would have to increase by 2% to reach the same 20% target.

To overcome this unfair distribution, a target to halve N waste was seen as a more equitable approach as less waste means less action is needed. For example, to reduce N waste by 50%, a farm with higher N waste e.g., 100t N/yr would have to reduce by 50 t N/yr and a farm with less N waste e.g., 10 t N/yr would have to reduce by 5t N/yr. Therefore, the largest effort needed is placed on farms with higher N waste (low NUE) as opposed to farms already operating with high efficiency (high NUE).

Alongside the support from the UNEP and the technical support of the International Nitrogen Management System (INMS), the Colombo Declaration represents the first-time that governments are collaborating on an ambitious, quantitative, and global N management target by seeking to cut N waste by 50% across the world.

4.3.2. Outside Europe

New Zealand's Climate Change Response (Zero Carbon) Amendment Act 2019 includes a target to reduce N_2O emissions to net zero by 2050. Canada (which has set a target to reduce fertiliser emissions by 30% by 2030) applies a region-specific approach due to the vast expanse of the country having variable meteorological conditions.

4.3.3. The European Union

The Nitrates Directive (1991) aims to protect water quality across Europe by preventing nitrate losses from agricultural sources through the promotion of good farming practices and includes limitations on N application from manures. Nitrate Vulnerable Zones (NVZs) are areas where the water bodies, such as lakes or rivers, are considered 'at risk' because there they have more than 50 mg/l of NO_3^- or are eutrophic. Farmers in these areas must comply with rules set out in the Member States's action programmes to reduce the risk and the Managing Authorities need to report on NO_3^- concentrations in ground and surface waters. The Directive does not focus on N emissions other than NO_3^-. While the Nitrates Directive has driven a reduction in nutrient application over the last 30 years, targets have failed to improve NUE in many areas with reported high levels of N surplus (N remaining beyond plant and soil requirements) found in the Netherlands, Belgium, north-west Germany, Luxembourg and Brittany in France.

The National Emissions reduction Commitment (NEC) Directive (2016) is the current primary European regulation requiring actions to improve air quality and sets targets for reduction in the emissions of key air pollutants. This is important in an agricultural context due to the inclusion of setting reduction targets for NH_3. Target reductions are specific to each Member

State and vary significantly with the target NH_3 reduction for 2030 ranging from 1% for Estonia and 32% for Hungary.

The European Green Deal (2019) is the EU's holistic plan to achieve net zero GHG emissions across the EU, while improving biodiversity and human health. The Farm to Fork strategy (2020) includes targets to reduce the use of N fertilisers and losses of N to the environment to support improvements in air and water quality and to reduce emissions of GHGs. The strategy sets a target to reduce nutrient losses by at least 50%, while ensuring that there is no deterioration in soil fertility. The European Commission expect this to reduce the use of fertilisers by at least 20% by 2030.

Considering the European wide scope of the directives and strategies to reduce N pollution, our study findings were surprising in that examples of nationwide NUE targets are limited. Whilst no country has a standalone NUE target, some countries such as Ireland and Denmark have incorporated NUE as an 'action' as part of a programme or another target (e.g., GHG target).

The Danish example relates to the historic, 1980 'Good Agricultural Practice Program' where increasing NUE was part of a suite of actions to reduce N use. This program was unsuccessful in limiting emission effects and as such 'harmony rules' were introduced, which, along with other measures, increased the Danish national NUE to an average of 40%. The Danish harmony rules prescribe the minimum area that a livestock farm must have for spreading livestock manure from their livestock production, thus limiting N inputs to land from livestock manure (Sommer and Knudsen., 2021).

Ireland's Climate Action Plan 2021 put forward a suite of actions to deliver their GHG target that includes N. Action 359 details the implementation of 'a suite of measures to improve NUE'. Teagasc, who is leading this action, sees that there is room for improvement across Irish dairy farms with an industry target of 35% NUE "set for farmers to achieve in the coming years" – an improvement of 10% from the current NUE of 25%.

Also in 2021, Denmark introduced the 'Green transition of Danish agriculture' which has set an agricultural target to reduce GHG emissions by 55-60% by 2030, including a reduction of N emissions by 10,800 tonnes by 2027. The specific impacts on the aquatic environment are further covered through their Action Plan on the Aquatic Environment III which has targets to reduce N leaching.

France, through the French Climate and Resilience Law 2021, have set targets for reduction of N_2O emissions by 15% of 2015 levels and NH_3 emissions by 13% of 2005 levels by 2030 (Hawley., 2022). This law includes measures to reduce the use of mineral N fertilisers.

4.3.4. The United Kingdom

In the UK, there are N relevant targets at both UK-wide and devolved levels. Nitrate vulnerable zones (NVZ), designated as part of the Nitrates Directive (1991), aim to reduce nitrate water pollution by encouraging good farming practice. Areas where the concentration of nitrate in water exceed 50 mg/l in ground and/or surface waters have been designated as NVZs. There are at least 70 NVZs in England and Wales, covering 55% of agricultural land in England and 2.3% of Wales. Five areas of Scotland (Lower Nithsdale, Lothian and Borders, Strathmore and Fife (including Finavon), Moray, Aberdeenshire / Banff and Buchan, and Stranraer Lowlands) have been designated as NVZs.

The National Emissions Ceilings Regulations (NECR) (2018) commits the UK to reduce NH_3 of 8% by 2020 and 16% by 2030, both relative to 2005 levels. The 2020 target was not met, but there has been a 12% reduction since 2005[2].**Error! Bookmark not defined.** The NECR also contains reduction targets for nitrogen oxides (NO_x), of 55% by 2020 (which was met) and 73% by 2030 but agriculture is a less important source.

Wales have set a target of reducing its total agriculture specific GHG emissions by 28% by 2030 compared to 1990. There are currently no UK-wide agriculture specific GHG emissions reduction targets, however, there is a UK-wide target of net zero by 2050, and agriculture will play an important role in achieving this target. For example, Defra has implemented new regulations on the use of urea fertilisers from 2023, which means that only urease-inhibitor treated or protected urea fertilisers may be used throughout the year, while untreated/unprotected urea fertilisers may only to be used from 15th January to 31st March each year. This regulation is expected to deliver an 11kt reduction in ammonia emissions by 2024/2025.

4.4. Why set a NUE target in Scotland?

It is important to consider the size and balance of the different Scottish agricultural sectors to understand the NUE potential of each sector. This section provides detail on the different forms of N found in Scottish agriculture, their impact on flows of N and how they can be targeted to improve NUE. A list of mitigation measures to improve NUE can be found in Appendix E and the impacts of these measures on NUE in Scotland are discussed in section 6.2.

The most recent Scottish GHG Statistics (2021) states that 2MtCO_2e of N_2O was emitted from the agricultural sector, which is a quarter of Scotland's agriculture sector's total GHG emissions and 2/3rds of total N_2O emissions. N_2O is emitted from soils after the application of N-fertilisers and manures (Brown, 2021). In addition, 90% of Scotland's total NH_3 emissions are attributed to the agricultural sector. Tackling the emissions of these pollutants will directly contribute to the following Scottish Government policies and ambitions:

- The Nitrates Directive is the basis of Scotland's five NVZs under the Nitrate Vulnerable Zones (Scotland) Regulations 2008[3],
- the Scottish Government's Biodiversity strategy to 2045: tackling the nature emergency, has the ambition of "restored and regenerated biodiversity across the country by 2045",

[2] The 2021 total is an adjusted total to consider compliance, meaning the contribution of emissions from non-manure digestate spreading is removed

[3] A NVZ designation limits the total amount of N (from livestock manure) that can be applied to agricultural land in that area. Scottish NVZ designation is reviewed every four years and nitrate concentrations in surface and ground water are measured by The Scottish Environment Protection Agency (SEPA).

- the Scottish Government's Cleaner Air for Scotland 2 delivery plan
- the Pollution Prevention and Control (Scotland) Regulations 2012,
- target 7 of the Kunming-Montreal Global Biodiversity Framework to 'reduce excess nutrients lost to the environment by at least half including through more efficient nutrient cycling and use'. The UK is a signatory to this framework and Scotland signed the associated Edinburgh Declaration,
- National GHG targets set by the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019
- the CCPu sets out an ambition for the Scottish agriculture sector to reduce emissions by 31% from 2019 levels by 2032, and a commitment to "work with the agriculture and science sectors regarding the feasibility and development of a SMART target for reducing Scotland's emissions from nitrogen (N) fertiliser."

4.4.1. Understanding N flows in Scotland

In recognition of the potential for reducing N to reduce total GHG emissions, the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 set requirements for Scottish Ministers to create a Scottish Nitrogen Balance Sheet (SNBS) from 2022 (Figure 3). The N flows in the SNBS combine data across all sectors of the economy and environment forming an evidence base to support the optimal use of N across all economic sectors to achieve optimal economic and environmental outcomes. While the SNBS was published in 2022, the data within it relates to 2019. Scotland is currently the only country to have planned to regularly update a cross-economy and cross-environment N balance sheet.

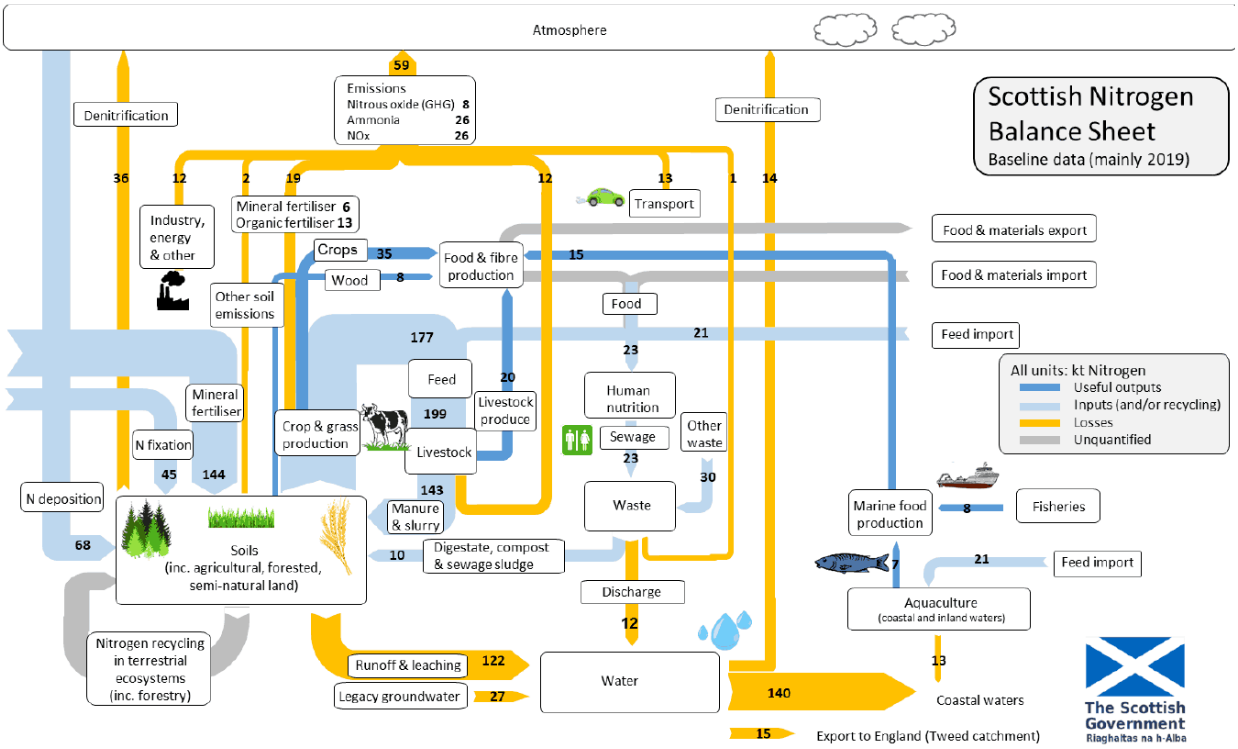


Figure 3. Scottish Nitrogen Balance Sheet (baseline data (mainly 2019)). Source: 3. Results from the initial version of the Scottish Nitrogen Balance Sheet - Establishing a Scottish Nitrogen Balance Sheet - gov.scot (www.gov.scot)

The annual SNBS report to the Scottish Parliament presents an assessment of:

- progress towards implementing proposals and policies relevant to improving NUE in Scotland,
- any future opportunities for improving NUE in Scotland, and
- how NUE is expected to contribute to the achievement of future emissions reduction targets (as per section 98 of the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019)

In 2022, the SNBS report published NUE values for agriculture as a whole sector (27%) with more granular figures of 65% for crop production NUE and 10% for livestock feed conversion. This valuable baseline shows NUE's potential for improvement which can reduce emissions from all forms of N to support improvements in air and water quality with positive implications to both human (Pozzer et al., 2017) and biodiversity health (Houlton et al., 2019). While the SNBS is a valuable baseline for improving N management it is important to note the specificities of its set-up particularly on how different quantities of N are attributed to different sectors and how this relates to what happens in practice (more detail on this can be found in Section 6.5).

Research has found that the global arable NUE is 35%. When we do not consider all the variables which impact NUE and NUE target setting, as discussed in sections 3.2 and 4.2, the Scottish arable NUE of 65% appears to compare well to international data, however, some EU countries have arable NUEs of up to 77%, showing there may be room for improvement. The 2022 SNBS report states total N losses from agriculture to the environment amount to 30.2 kt N/yr as air pollutants (NH_3, nitrogen dioxide (NO_2) and N_2O) and 104 kt N/yr from runoff and leaching from agricultural soils.

4.4.2. Targeting different forms of N

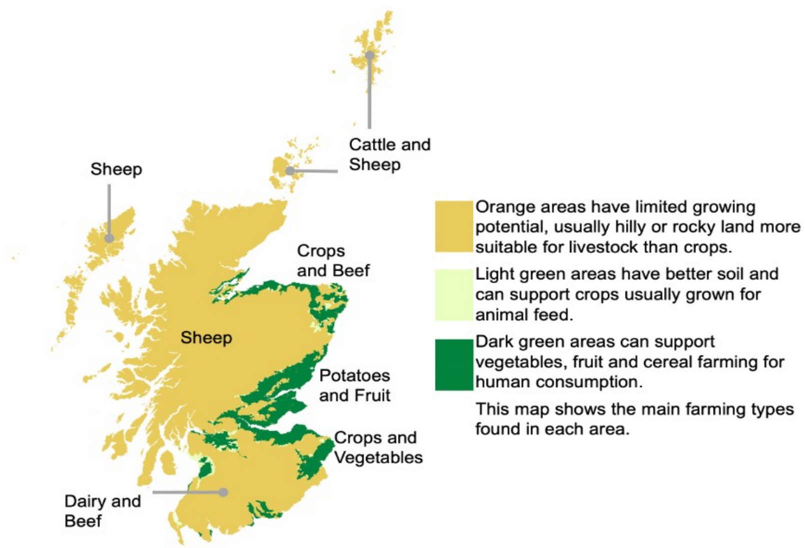


Figure 4 Scottish agricultural sectors (Scottish Agricultural Census June 2021)

The different N inputs and outputs of Scottish agriculture are described below (also see Figure 3). Most of Scotland's 5.64 million ha of agricultural area is best suited to livestock farming with a significant proportion occupied by cattle and sheep in Less Favoured Areas (LFAs) (55% or 3,159,137 ha) followed by crops and grass (1,885,701 ha), shown in Figure 4. Non-LFA cattle and sheep (107,712 ha) and specialist dairy (106,935 ha) are large sources of N in manure. More intensive sectors such as pigs and poultry do not have a direct correlation between NUE and land area, however they are significant sources of manures and contribute to N inputs. These areas are used to track N flows from the SNBS against sectors of particular potential in section 4.4.2. Note that forestry and aquaculture are out of scope of this project but will have impacts on Scottish N flows.

NUE varies between different Scottish farm types as the biological utilisation of N influences the potential NUE. The SNBS shows that livestock farms currently have a lower NUE (10%) than arable farms (65%). This is partly due to the relative inefficiency in the conversion of ingested N in feed converting to stable N within livestock products (milk and meat).

4.5. N Inputs

4.5.1. Fertiliser as the N input

The SNBS details that one of the largest flows of N in Scotland (143.8 kt N/y) is the use of inorganic fertiliser on arable crops and grass, with 62.1kt of this inorganic N applied to crops per year and 81.7kt going to grass [4]. The British Survey of Fertiliser practice states that in 2022, 63 kg N/ha were applied on average to all crops and grass in Scotland.

There is little information on N use in Scottish horticulture and permanent crops. Nonetheless, N fertiliser recommendations for vegetables, minority arable crops, bulbs, soft fruit and rhubarb crops exist. The high value of many of these crops and the technological advances taking place in this sector facilitate a higher degree of precision in management (e.g., GPS use for N application, leaf N monitoring, fertiliser application within irrigation water etc), which allows a better understanding of N flows in these systems. Targeted N applications could lead to reductions in inputs and waste thereby improving overall NUE for these crops. However, to date there are no recommended NUE levels for these specialist crops, thus more research is needed to understand the impact of reduced N applications on crop health and yield.

The evidence relating to the N requirements for the majority of crop and grass areas in Scotland is well described within the technical notes, and recommendations for NUE targets could build upon the evidence supporting these recommendations. Like specialist crops, improvements in fertiliser practices and technology can support improvements in N applications which will help matching of N inputs to crop requirements with greater precision and thus improves NUE.

[4] N fertilisers are used most commonly in the forms of ammonium nitrate and to a lesser extent urea both as a solid prill (pellet) which is spread using a broadcast spreader.

4.5.2. Livestock Feed intake as the N input

The optimum levels for dietary crude protein are often exceeded to ensure that N intake does not limit either growth or welfare. This excess of N supply in the diet results in surplus N being excreted through manure and urine leading to N losses. Cattle cannot efficiently convert dietary N (efficiency ranging between 22-33%) and therefore, on average, 75% of consumed N is wasted, mainly through excretion. Matching N supply in feed with livestock requirements is part of 'precision livestock feeding' which can increase farm profitability, reduce emission intensity of methane (Rooke et al., 2016) and reduce N intake and excretion. Reductions to NH_3 and N_2O emissions from livestock sources due to precision feeding vary widely. However, studies have found that a reduction in crude protein of 2% leads to a 24% reduction in NH_3 emissions in broilers, and a 1% crude protein reduction in pig feed results in a 10% reduction in NH_3 emissions (Santonja, 2017).

The SNBS found one of the largest N flows is N excreted by livestock (142.9 kt N/y). The control of N levels added to soil from livestock directly impacts the input part of the livestock NUE calculation. A NUE target aimed at the livestock sector may be most impactful as it currently has the lowest NUE (10%) whilst also covering the largest amount of agricultural land (combined total of 3.3 million ha) meaning even a small, targeted improvement in NUE for livestock could have a significant impact on the overall N budget.

4.6. N Outputs

4.6.1. Ammonia as the output

NH_3 from agricultural sources produces particulate matter which can impact human health, causing diseases such as cardiovascular and respiratory disease. In addition, NH_3 emissions can result in the long-range transport of N compounds and this N deposition can cause acidification and eutrophication. Scottish agriculture accounts for 90% of total NH_3 emissions, which have decreased by 12% over the last 30 years. NH_3 is tied specifically to the (housed) livestock sector, with most emissions (35% of NH_3 emissions) coming from cattle manure management. Livestock housing and storage of manure is responsible for 10.5kt N/y in the form of NH_3 emissions, therefore improvements targeted at this sector would directly improve NUE. Examples of mitigation measures which can be introduced to lower the NH_3 emissions in this sector are detailed in Table 3 under section 6.2.1 and include slurry store covers and slurry acidification.

Use of urea based inorganic fertilisers can lead to significant losses of NH_3. High temperatures and winds at the time of fertiliser application or very dry conditions can lead to high levels of NH_3 volatilisation (the conversion of NH_4+ to NH_3 gas) with a significant proportion of the N being lost and unavailable to the plants. A useful mitigation measure is the use of urease inhibitors with urea fertilisers to reduce these emissions.

4.6.2. Nitrate leaching as the output

Excessive leaching of N from agricultural activity can lead to water pollution and eutrophication which can then result in the loss of aquatic biodiversity and GHG emissions.

The SNBS shows N run-off and leaching from crops and arable land as 45.5 kt N/yr and from grass as 58.5 kt N/yr. This N is lost as NO_3^-, which is readily mobile in soil water or runoff. Any N that is lost from the soil is no longer available to plants thereby lowering the potential NUE and increasing agricultural pollution.

According to Adaptation Scotland, Scotland is predicted to experience an increase in rainfall, with intense, heavy rainfall events increasing in both winter and summer. This has the potential to increase N leaching as soil moisture controls both crop N uptake and N leaching (McKay Fletcher et al., 2022). In addition, Scotland's topography affects the rate of run-off as steep slopes promote surface run-off. When considering Scotland's topography and the predicted change in rainfall, the potential for leaching will increase and continue to negatively affect water quality. Those areas currently most at risk are classified as NVZs.

4.6.3. Nitrous oxide emissions as the output

N_2O is a GHG that accumulates in the atmosphere and directly contributes to climate change. The SNBS shows 5.9kt N_2O per year is emitted from the agriculture sector. This includes 0.9kt from livestock (including manure management), 3.8kt from soil management (including mineral fertiliser use), and 1.2kt of indirect emissions (from N deposition and NO_3^- leaching). N_2O is produced in the process of denitrification, where denitrifying bacteria under conditions where oxygen is limited (for example waterlogged soils) use the NO_3^- available in soil. By using the NO_3^- in soil, these bacteria reduce the NO_3^- available by plants potentially negatively impacting yield. In conditions where NO_3^- is available in excess denitrification can reduce NO_3^- losses through leaching. However, since N_2O is produced in the process, negative impacts on climate are the result. Total elimination of N_2O emissions from agriculture is not possible; however, some mitigation is possible through improvements in soil conditions and avoidance of N fertiliser application under wet conditions (Munch and Velthof, 2007).

4.6.4. Crop and livestock outputs

Crop and livestock products are the useful outputs of N from agriculture. In Scotland these account for 54.5kt N per year. This value includes livestock products, including meat, milk, eggs, and wool, and harvested crops used for food for human consumption (but excludes crops for animal feed or fodder). Useful crop outputs also include seed, feed and straw, but these are retained in the agricultural system and so are not final outputs.

Cereals, explicitly for alcohol production, accounts for the largest useful output flow in Scotland at 20.5kt N, followed by livestock products at 19.6kt N and crop product for human consumption at 12.2kt N (all values per year).

Optimising the quantity of N recovered in these outputs i.e. the N is taken up by the plant or animal and used to increase growth, relative to the quantity of inputs (feed and fertiliser) is key to reducing N waste and improving NUE. Managing the quantity of N application to meet crop and livestock requirements alongside the soil conditions will improve the overall NUE.

5. Viability of a SMART Target for NUE in Scotland

This section looks at the viability of setting a NUE target for Scotland and provides a summary of the risks and benefits of setting a Specific, Measurable, Achievable, Relevant, and Time-Bound (SMART) NUE target in Scotland and presents how a range of influences can support or hinder the achievement of a NUE target. Information on N targets in other countries was considered and analysed for their applicability to Scotland. Since no other country has a standalone NUE target, we had to rely on information on other N targets for our analysis and transfer these finding to a NUE target for Scotland. The methodology can be found in Appendix F.

5.1. Analysis Tools

5.1.1. SWOT analysis

Strengths, weaknesses, opportunities, and threats (SWOT) of setting N-related targets were analysed based on the information gathered on N targets in other countries. We also included analysis of GHG and climate related targets where relevant to increase the body of information. This information was then used to assess applicability of setting a NUE target for Scottish agriculture with the limitation that the analysis was based on N, GHG and climate related, rather than NUE specific targets. The SWOT analysis shows a range of influences which can support or hinder the achievement of a NUE target. The full SWOT analysis can be found in Appendix F.

5.1.2. PESTLE analysis

Setting NUE and other N targets are subject to a range of enablers and barriers. Therefore, a political, economic, social, technical, legal, and environmental (PESTLE) analysis was undertaken to assess the feasibility of setting a NUE target for Scottish agriculture, again, with the limitation that the analysis was based on N, GHG and climate related rather than NUE specific targets. The PESTLE assessment took place following the SWOT analysis to ensure the findings from the SWOT were assessed and, if relevant, included into the PESTLE categories. The full PESTLE analysis can be found in Appendix F.

5.2. Discussion

5.2.1. Supporting a SMART NUE target

The SNBS[Error! Bookmark not defined.] is reviewed and updated annually and provides a source of data for measuring and monitoring the changes in NUE and thus the progression of a NUE target. In addition, all mitigation measures identified in section 6.2 and analysed for their effect on Scottish agriculture NUE are captured by the SNBS. The use of the SNBS enables a **measurable** target**.** This was identified as a strength and technical enabler in the analysis of setting a NUE target.

Another strength and technical enabler identified through the analysis includes the mitigation measures required to achieve a NUE target. N-related mitigation measures are well understood, and many are relatively low cost and already practiced in Scottish agriculture (e.g., use of catch and cover crops) which makes reduction in N losses **achievable**. Furthermore, measures continue to be developed through additional research e.g. in Canada to understand the emission reduction potential, costs and benefits of different measures at farm level.

Section 6.4 recommends years 2030, 2040 and 2045 as deadlines which would ensure a NUE target is **time-bound**. These years align with other emission targets set in Scottish Government which may affect agriculture and therefore complement a new, potential NUE target. Including three timed steps into a binding target would also help **measure** the progression of the NUE target whilst also encouraging the delivery of high reductions.

A NUE target would be **relevant** in meeting statutory emission reduction targets. Introducing a NUE target would lower N-related emissions and would therefore contribute to other emissions reduction targets, for example the CCPu**Error! Bookmark not defined.** which aims to reduce agricultural GHG emissions by 31% from 2019 levels by 2032. Similarly, a NUE target would be **relevant** to several other environmental issues as the implementation and success of a NUE target would have multiple benefits for example, improvements to water quality, air quality (Sutton et al., 2014), human health and biodiversity (Houlton et al., 2019).

The SWOT and PESTLE analysis identified influences needed to support a **specific** and **achievable** NUE target by detailing opportunities which could assist with the implementation of such a target. Regulatory instruments include BAT/mitigation measures and fertiliser use limits, economic instruments include taxes and subsidies, and communicative instruments include extension services and awareness (Oenema et al., 2011).

Other positive influences include an increase in farm profitability following the implementation of mitigation measures such as precision livestock feeding and matching N supply to demand) which was found as a strength and economic enabler through the analysis. Moreover, through the introduction of a NUE target, there would be an opportunity to involve advisors and consultants which may also lead to the implementation of better advice and practice regarding N use in Scottish agriculture.

5.2.2. Hindering a SMART NUE target

All analysis was based on N targets rather than NUE targets due to the lack of any NUE specific targets in other countries. Therefore, clear evidence on NUE targets ***is lacking*** and the analysis of a NUE target for Scotland is based on assumptions through transferring information from N-related targets to NUE.

To achieve any potential NUE targets a range of new techniques, technologies and systems would be required. These are referred to as mitigation measures. There is already a good body of evidence and supporting examples of the implementation of mitigations. These have been identified as a strength and enabler as some examples such as variable rate N application (precision farming) can save farmers money on inputs by only purchasing and applying N as needed. Others, however, require significant capital expenditure with upfront investment of time and money required to implement some of the mitigation measures (for example, low emission slurry application equipment). This has also been identified as a weakness and economic barrier which may be experienced by Scottish farmers. This could directly impact upon the **achievability** of a NUE target. Similarly, several barriers to uptake of mitigation measures were identified as a threat through the SWOT analysis. Barriers include lack of awareness and knowledge of why and how to improve N use, and farmer's personal beliefs, both of which may lead to Scottish farm managers finding it difficult to quantify the benefits to their business and understand the **relevance** of a NUE target. These barriers would generally hinder the **achievability** of a NUE target.

In trying to make a NUE target **relevant** in terms of meeting statutory emission reduction targets, there is a risk when reducing N-related emissions, through mitigation measures, that pollution-swapping takes place. An example of this is the decrease in NH_3 emissions and an increase in N_2O emissions (due to nitrification/denitrification processes) when using slurry injection (a type of low emission slurry application) compared to surface application. Pollution-swapping as an unintended consequence of some mitigation measures was identified as a threat and environmental barrier in introducing a NUE target.

Farmers' perception of a national NUE target for Scotland may limit target **achievability**. Scottish farmers may not understand how their practices impact NUE and how introducing on-farm mitigation measures may impact on a general NUE target for Scottish agriculture. For example, questions may arise on how many and at what frequency the relevant mitigation measures need to be introduced by each farmer to achieve this overarching target. To overcome this, some farmers may respond more positively to several more **specific** targets, for example a reduction of fertiliser input (by a certain amount and by a certain date). Alternatively, ensuring a NUE target is accompanied with very **specific** and **relevant** action points on how this NUE target would be achieved so that farmers have a clear understanding on what is expected of them and their farming system to contribute to a national NUE target.

The time taken to create and process the appropriate legislation for a NUE target can be uncertain and longwinded. This process has the potential to directly impact the **time-bound** element of a SMART NUE target.

In the Netherlands, an ambitious target led to civil unrest where more than 10,000 Dutch farmers have been protesting following government plans to reduce N emissions. Similarly, when targets or limits are seen to be a barrier to economic performance, implementation of new regulation can become challenging, as is seen in the case of revising the approach towards Nutrient Neutrality in England. The use of a SMART target is therefore critical to avoid the implementation of a policy which is neither appropriate nor achievable.

In the main, these examples relate to current exceedances of regulations under the Habitats or Nitrates directives, follow a long period of previous actions and constraints on the farming sector and relate to farming systems which are very different to those present within Scotland. In addition, these regulations are not focused on NUE but rather on the achievement of environmental targets and so do not consider the productive potential of the sector. Notwithstanding these differences, these risks do indicate the importance of well formulated targets, based on sound scientific understanding and with a clear plan for consultation and implementation on their achievement and delivery.

The political and legal barriers identified include the potential for pushback on mitigation measures which are seen to reduce productive output and a concern that Scottish farmers may not comply with regulatory requirements. This could directly impact upon the **achievability** of a NUE target.

6. Development of a NUE target for Scotland

6.1. Assessment using the Scottish Nitrogen Balance Sheet

The SNBS has been used as a baseline to assess how practices that influence N pools or flows may impact the agricultural NUE value. This dataset contains values for key sectors, pools (stores of N within parts of the N cycle e.g. in manure, in soils or in livestock/crops), and flows of N (movement of N into different pools as the N form changes or is taken up by plant or animals). These flows include inputs to the system (e.g. fertilisers, animal feed), useful outputs (e.g. meat, cereals), and waste (e.g. NO_3^- leaching, NH_3 emissions). Each of these flows have a value in kt N/yr assigned. The NUE is improved by either increasing the output flow values or reducing input and waste flow values. This can be modelled by estimating the impact of a mitigation measure (e.g. improved nutrient planning or reduced protein livestock feed) and applying these values to the relevant N flow in the SNBS (for improved nutrient planning this would be reduced inputs of fertiliser and reduced N emissions to atmosphere). This produces estimates for N flows that can then be summarised in NUE calculations as currently setup in the SNBS, resulting in estimates of improved NUE values (see Appendix E for a detailed methodology and all assumptions).

6.2. Mitigation measures

6.2.1. The effect of mitigation measures on Scottish agriculture’s NUE

This section presents and discusses the effects of 18 different mitigation measures on the current NUE of Scottish agriculture.

The table below presents modelled estimates for the NUE of Scottish agriculture, by individual measure and at each future projected target year. The values reflect implementing the relevant measure individually and compared to the current whole-agriculture NUE of 27.2% (i.e. preventing soil compaction may improve total NUE by 0.1% by 2030). The results show the impact for the relevant measure in isolation and do not reflect any combination effects for interactions with other measures. Further detail on the assumptions and methodology can be found in Appendix E. The 2030, 2040 and 2045 scenarios are based on minimal change, continuing recent trends of recent changes in uptake, but including greater increases where there is precedent to, e.g. low emissions spreading techniques all increasing to 95% by 2030 as this will be required under the New General Binding Rules on Silage and Slurry. However, the 2045 Ambitious scenario is based on a transformational change across the sector where there is greater effort to improve

NUE to meet a legally binding target. Therefore, the improved NUE in the 2045 and 2045 (Ambitious) scenarios may be viewed as the range where a target may be set, where the lower bound of the range (2045 scenario) is more achievable, while the higher bound (2045 (Ambitious) scenario) would require more effort across stakeholders to be achieved but is a better value.

Table 3 List of mitigation measures and their effect on Scottish agriculture NUE (%) compared to the current whole agriculture NUE of 27.2%. The two 2045 scenarios can be viewed as an ideal range for NUE; where the lower bound (2045 scenario) reflects changes to agriculture planned to come in (current and upcoming legislation, expert judgement on technological developments etc.); while the upper bound (2045 ambitious scenario) reflects the possibility for a greater push from industry and government to improve NUE (financial incentives, increased awareness of N management, etc.).

Measure	2030	2040	2045	2045 (Ambitious)
Avoid excess N	31.23% (-3.02%)	31.90% (-3.48%)	31.90% (-3.48%)	33/41% (-5.59%)
VRNT	27.66% (-0.43%)	27.96% (-0.72%)	28.41% (-1.16%)	30.40% (-3.02%)
Urease Inhibitors	27.57% (-0.35%)	28.08% (-0.86%)	28.35% (-1.12%)	28.70% (-1.47%)
Improving nutrition	27.26% (-0.03%)	27.30% (-0.07%)	28.27% (-1.04%)	28.26% (-1.03%)
Novel crops	27.44% (-0.22%)	27.52% (-0.29%)	27.77% (-0.55%)	27.81% (-0.58%)
Low emission spreading	27.62% (-0.39%)	27.62% (-0.39%)	27.62% (-0.39%)	27.62% (-0.39%)
Rapid incorporation	27.26% (-0.09%)	27.31% (-0.09%)	27.34% (-0.11%)	27.47% (-0.24%)
Low emission housing	27.24% (-0.02%)	27.27% (-0.04%)	27.28% (-0.06%)	27.43% (-0.20%)
Improving livestock health	27.64% (-0.42%)	28.02% (-0.80%)	27.32% (-0.09%)	27.43% (-0.20%)
Slurry cover	27.25% (-0.02%)	27.28% (-0.05%)	27.03% (-0.07%)	27.33% (-0.10%)
Optimal soil pH	27.25% (-0.02%)	27.29% (-0.06%)	27.30% (-0.07%)	27.30% (-0.07%)
Nitrification inhibitor	27.23% (-0.01%)	27.24% (-0.02%)	27.25% (-0.02%)	27.25% (-0.03%)
Improving GI + genomic tools	27.23% (0.00%)	27.23% (-0.01%)	27.23% (-0.01%)	27.25% (-0.03%)
Slurry acidification	27.23% (0.00%)	27.24% (-0.01%)	27.24% (-0.01%)	27.25% (-0.02%)
Preventing soil compaction	27.23% (-0.01%)	27.24% (-0.01%)	27.24% (-0.02%)	27.24% (-0.02%)
Use of catch and cover crops	27.27% (-0.05%)	27.34% (-0.11%)	27.37% (-0.15%)	27.38% (-0.18%)
Legume-grass mixtures	-	-	-	-
Grain legumes in crop rotations	-	-	-	-

There are potential interactions/overlaps between several of these measures. Where this occurs, measures cannot be applied on the same unit (area of land/head of livestock) at the same time as they are mutually exclusive. We have avoided double counting these effects by resolving the total maximum applicability across overlapping measures i.e. the combination of measures cannot exceed the total land available to apply the measure to.

The key outcomes are:

- The measures with the greatest potential improvement on NUE are nitrification inhibitors, improving livestock nutrition, and improving livestock health.
- Nitrification inhibitors are more effective at improving NUE than urease inhibitors as they can be applied to a greater proportion of fertiliser products used in Scotland (both NO_3^- and urea-based products, while urease inhibitor can only be applied to urea-based products).
- Improving livestock nutrition will improve NUE by reducing the overall quantity of N being fed to livestock while maintaining liveweight yield.

Measures that are based on the use of legume crops were not included in the modelling of the new NUE values, as the reduced requirement for inorganic fertiliser input will be offset by increased biological fixation of N from the atmosphere. Both flows are included in the N input values when calculating NUE in the SNBS. Therefore, the total N inputs levels will stay constant, as will the outputs, and so there is no impact on NUE. However, there are benefits of legume crops beyond an improvement to NUE, which should be considered, namely the effects of reduced requirement for inorganic fertiliser inputs (lower GHG emissions), improved soil health and soil function, and reduced costs. This is likely to be economically beneficial to the farmer, as soil health benefits the local ecosystem and improves resilience, reduced fertiliser use avoids emissions from manufacture and transportation of inorganic fertiliser; all of which are benefits from moving to a circular economy.

6.2.2. Potential N savings through implementation

The table below summarises the potential savings of N inputs of mineral fertiliser in both absolute values in kt N yr^{-1}, and relative to the quantity in the current SNBS as a %. The values presented here include fertiliser use savings due to legume-based measures (legume-grass mixtures, and legumes in crop rotations). The effect of these measures is not included in calculations of NUE due to the assumption that the saved fertiliser N application will be replaced by increased N deposition from the atmosphere.

Table 4 Absolute values of N inputs of mineral fertiliser saved in kt N per year and as % of the quantity in the current SNBS when all modelled measures are included. The two 2045 scenarios can be viewed as an ideal range for NUE; where the lower bound (2045 scenario) reflects changes to agriculture planned to come in (current and upcoming legislation, expert judgement on technological developments etc.); while the upper bound (2045 ambitious scenario) reflects the possibility for a greater push from industry and government to improve NUE (financial incentives, increased awareness of N management, etc.).

Year	2021 (kt N yr^{-1})	Savings (kt N yr^{-1})	Savings (%)	Savings (kt CO_2e yr^{-1})
2030	143.78	36.36	25.29	160.09
2040	143.78	44.16	32.12	213.41
2045	143.78	53.14	37.96	248.56
2045 (Ambitious)	143.78	78.22	-54.40	361.15

6.3. Recommended criteria for target(s) setting for Scotland

When modelling the NUE improvements and the establishment of potential targets, the key criteria for consideration are listed below.

6.3.1. Mitigation measures

The measures/farming practices that have been included for modelling are the result of literature searches and expert judgement. Measures that impact N flows in agricultural systems, and the relevant data, were extracted from literature. These were then reviewed to ensure applicability to Scotland, and any other measures that were identified by experts as being important were also researched.

6.3.2. Current uptake

The current uptake provides a basis from which to estimate what future uptake may be possible and the likely rate of additional implementation. It also supports the calculation of a baseline or counterfactual against which change can be measured. These values come from the same sources which have provided the NUE impact values (see Appendix E for detail on current uptake for each measure).

6.3.3. Applicability

The applicability values refer to the portion of a SNBS N flow that a measure's impact value can apply to. Expected future uptake

The expected future uptake values are estimates based on expert judgment and consultation within the project team. The values for each measure can be found in Appendix E and are additional to the current uptake levels. These values increase over time to reflect increasing commitment to NUE improvements. The two 2045 scenarios can be viewed as an ideal range for NUE; where the lower bound (2045 scenario) reflects changes to agriculture planned to come in (current and upcoming legislation, expert judgement on technological developments etc.); while the upper bound (2045 ambitious scenario) reflects the possibility for a greater push from industry and government to improve NUE (financial incentives, increased awareness of N management, etc.). The expected future uptake ranges from 1% to 100% depending on the measure and scenario. For example, soil compaction was only expected to increase by 2% even in the 2045 (Ambitious) scenario as it was assumed that where soil compaction is occurring most farmers will already be taking steps to improve it. While low emission spreading techniques increased to 95% by 2030 to reflect the New General Binding Rules on Silage and Slurry. A full example is provided in Appendix G.

6.3.4. Timescales

We modelled potential NUE targets for Scottish agriculture for 2030, 2040, and 2045. These were chosen to align with Scotland's Climate Change Act 2019 with a target date of 2045 for reaching net zero GHG emissions.

6.3.5. One NUE target for Scottish agriculture or per sector?

Currently, the arable sector is more N efficient than the livestock sector (65% and 10% respectively)[Error! Bookmark not defined.]. This difference is due to inherent qualities of livestock systems with animals unable to process N as protein as efficiently as plants uptake N. The current NUE should, however, be seen as a baseline, and the scale of improvements from this should be the focus rather than an absolute target applicable to all sectors and systems. The majority of measures included in the modelling of NUE improvements target the soil N pools (arable and grass land), therefore separate targets for each sector are advisable.

6.4. Analysis of recommendations

The table below presents the estimated NUE values in 2030, 2040, and 2045 based on increased uptake of on-farm measures. As well as an additional value for the year 2045 where increased ambition has been included in the projected uptake values.

Table 5. Potentially achievable NUE estimates in 2030, 2040 and 2054 based on increased uptake of on-farm measures. The two 2045 scenarios can be viewed as an ideal range for NUE; where the lower bound (2045 scenario) reflects changes to agriculture planned to come in (current and upcoming legislation, expert judgement on technological developments etc.); while the upper bound (2045 ambitious scenario) reflects the possibility for a greater push from industry and government to improve NUE (financial incentives, increased awareness of N management, etc.).

	Potentially achievable NUE estimates (%)				
	2021 (Current)	2030	2040	2045	2045 (Ambitious)
Whole agriculture	27.2	33.7	35.7	38.2	40.9

The NUE values that are modelled in this study are based on the selected measures, and the achievement of these NUE targets rely on their implementation. Other agricultural practices may impact N flows, as will changes in the size of agricultural sectors.

Similarly, the NUE values that have been calculated are based on the levels of implementation that have been included in the modelling. Achieving these targets in practice will require supporting instruments to encourage the uptake of these measures. As stated in Section 6.2.1, the NUE values in the above table for 2030 and 2040 reflect assumptions on uptake based on minimal change and not a transformational change to the sector (such as the setting of a target). Therefore, these values should not be viewed as potential targets for these years, but as indicators of the feasibility of improvements to NUE in Scottish agriculture.

Sector specific NUE values are not currently feasible due to the calculation set-up in the current SNBS (which flows are considered as inputs/outputs for arable and livestock), and the assumption made in the modelling that production will not increase and only inputs will decrease. This set-up leads to results that make it seem that the arable sector is mining N, which is not the case. Improvements to the set-up of calculations to overcome this barrier are outlined in Section 6.5 below.

6.5. Guidance for future implementation

In the current version of the SNBS, the NUE calculations do not align directly with what happens in practice in the different agricultural sectors because there are overlaps and movements of N flows between the different agricultural sectors that are not easily viewed in isolation. For example, in practice, improvements to NUE due to implementation of manure management measures will largely be implemented by the livestock sector. However, given the current set-up of the calculations in the SNBS, N flows related to manure management may not be attributed to the livestock sector NUE values as they will reduce emissions from spreading of organic matter to soils, which would be reported in the arable sector calculation. This would make it more difficult to use the SNBS to set and measure sectoral targets. Therefore, accurately monitoring the changes in NUE and attributing these changes to the correct sector would be important if considering sectoral targets. Accurately representing N flows in the SNBS to the relevant sector may be difficult, due to, for example, data availability, different ways data is collected across mitigation measures and sectors and difficulties in correctly separating overlaps and movements of N flows between the different agricultural sectors, however, could significantly help the feasibility of achieving and monitoring NUE targets.

When reflecting the potential impacts of mitigation measures on the values in the SNBS, certain hurdles resulting from the disaggregation of flows make it more difficult and possibly less accurate. More details of these hurdles, and how they were overcome, can be found in Appendix E, but a key example here is the use of slurry acidification on livestock slurry. In the SNBS there is one flow of N from manure management to atmosphere which includes all manure storage types and all livestock types. However, the implementation potential and mitigation impact potential will vary between storage and livestock types. This required an assumption to be made on the breakdown of this manure management N flow so that the appropriate uptake levels and impact values can be applied to the correct portion of the total N value (in this instance the Scottish Agricultural Census was used). This can be considered a sound approach to reflect the mitigation measures in the current SNBS, however going forward, to improve the ease and accuracy with which targets can be projected and improvements can be measured, a more granular breakdown on the N flows in the agricultural sector in the SNBS are required.

7. Conclusions

7.1. A NUE target for Scotland

The rationale behind setting a NUE target for Scotland is to reduce the impacts of N wastages to the environment **to lower GHG emissions and improve water and air quality**. NUE values can be used as indicators for N resource use efficiency and as markers for improvement. Scotland is in the unique position to use and regularly update a cross-economy and cross-environment N Balance Sheet (SNBS). The SNBS provides a valuable baseline in the current performance of Scottish agriculture and provides a tool to tackle all forms of N pollution.

However, setting a NUE target is not without challenges and nowhere in the world has yet set a NUE target. NUE values are impacted by various factors (soil type, climate, crop type, livestock type, etc). Whilst research shows that **the ideal range for NUE is between 50-90%**, it is crucial to understand the different forms of N inputs and outputs and to allocate these correctly to the different farming sectors.

As **no other country has yet set a standalone NUE target**, we had to solely rely on other N-related targets for our evidence base. Our analysis of the viability of setting a NUE target for Scotland is therefore based on assumptions through transferring information from N-related targets to NUE.

The SWOT and PESTLE analysis carried out in this study highlighted several factors which can influence the success of a SMART NUE target for Scottish agriculture. Importantly, **the use of the SNBS would make the target measurable and the fact that many N-related mitigation measures are well understood and already practiced** in Scottish agriculture would make the target achievable. However, some mitigation measures require significant **capital expenditure**, such as slurry management equipment, or increased ongoing investment, such as nitrification inhibitors, or a change in focus, such as better-balanced protein in livestock feed. These changes would need **support from the farming sector**. Using NVZ regulations as an example, a small study conducted in 2016 (Macgregor and Warren 2016) showed that some farmers regarded the NVZ regulations as “burdensome and costly”. To avoid similar responses to setting NUE targets, farmers would need to be able to quantify the benefits to their business and understand the relevance of a NUE target for climate and the environment. It is therefore important to accompany NUE targets with specific actions points expected by farming businesses. Providing funding to farmers to **help implement**

mitigation measures and share knowledge on the impact to their businesses, the climate, water quality, air quality and biodiversity is likely to aid faster and easier uptake of these measures.

Looking at initiatives worldwide, we know that N use can be targeted in many different forms (fertiliser use, livestock diet, reduction of N waste, reduction of emission of air pollutants, etc.) and alongside the proven mitigation measures discussed above, **it is clear that improvements to NUE are achievable**.

7.1.1. Modelling NUE improvements using the SNBS

In this study, the SNBS has been used to model NUE improvements by estimating the impact of a mitigation measure and applying these values to the relevant N flow in the SNBS. It is important to note that these results *show the impact for the relevant measure in isolation* so do not reflect any combination effects for interactions with other measures. In the arable sector, the mitigation measures with the greatest potential to improve NUE are the use of **variable rate N application (precision farming) and the use of nitrification inhibitors** potentially increasing NUE to 28.8% and 29.7%, respectively, by 2045. In the livestock sector, **improving nutrition and improving livestock health** (NUE of 31.7% and 29.4% respectively by 2045) have the greatest potential. Overall, the modelling suggests that total NUE of Scottish agriculture **could be increased to 38.2-40.9% by 2045**, depending on the level of implementation of mitigation measures.

Sector specific NUE values are not presently feasible due to the calculation set-up in the SNBS and the assumptions that production will remain stable, with only inputs decreasing. In the current version of the SNBS, the NUE calculations do not align directly with what happens in practice in the different agricultural sectors because there are overlaps and movements of N flows between the different agricultural sectors that are not easily viewed in isolation and not necessarily attributed to the correct sector. For example, mitigation measures around manure management will, in practice, be mainly implemented by the livestock sector but will, in the current calculations, be attributed to the arable sector because they are linked to reduced emissions from spreading of organic matter to soils.

7.2. The feasibility of a NUE target for Scotland

This research indicates that a NUE target for Scotland is not currently feasible. We see potential for such a target in the future but recommend to first consider several points for improvement.

1. **The SNBS.** Improvements to the calculations and attributions of flows of N to the different measures and sectors are required. The modelling for this report depends on assumptions and figures from another CXC report (Eory, et al., 2023). We recommend updating this data with real on farm data to better inform assumptions that follow from it.
2. **The sectors.** Currently, the arable sector is more N efficient than the livestock sector (65% and 10% respectively). Sector specific targets would be helpful due to

differences in current NUE, N inputs and N wastages but this is presently not possible due to the current limitations in the SNBS.

3. **The mitigation measures.** More data on the impacts of mitigation measures under Scottish conditions would increase the accuracy of modelling achievable aims. Since NUE values are both indicators of resource efficiency and markers for improvement, it is possible to focus on mitigation measures with the most potential to improve NUE values.
4. **Farmers.** It is highly important to ensure that targets and measures are clearly understandable and achievable for farmers to create support from the farming sector.

7.2.1. A potential target figure?

If a NUE target was set, this could be in line with the **modelled potential NUE estimates of 38.2-40.9%** by 2045, depending on mitigation measure implementation. To achieve greater improvement, a combined push from industry and government (financial incentives, increased awareness of N management, etc.) is required. This additional push is reflected in our 'Ambitious scenario'.

However, based on our research findings, the barriers identified to implementing an achievable and successful NUE target and the need for farmer and industry support to achieve changes in practices and expectations, we conclude that focusing on reducing N waste is likely to have more success than NUE targets as a policy option. Experience from the United Nations Environment Assembly's discussions on N and the Green Deal's Farm to Fork targets, has shown more success in including the reduction of N pollution in policy when focusing on **N waste** over NUE targets. NUE can instead be used as a technical tool to mark improvements, with the SNBS key to setting a baseline and providing a visualisation of the combined impacts of implemented mitigations measures over time. We therefore recommend **setting a target for N waste.**

7.3. An alternative - a N waste target?

Opportunities for setting a N waste reduction target include:

- It is an easier concept to communicate to the farming community and other N producing sectors.
- It gives the opportunity to value any N as a resource until it is lost as waste, creating options for greater collaboration between the arable, horticulture and livestock sectors. Any potential bias towards a sector will be avoided.
- Each individual farmer and land manager would be encouraged to reduce N waste for the economic and environmentally beneficial outcomes. The positive messages around a N waste target would be likely to create support from the farming sector.
- Achievements towards an N waste target would achieve reductions in national NUE thereby achieving the same objectives without the current issues around NUE targets.

Following the Colombo Declaration of 50% reduction of N waste and the Green Deal target of reducing nutrient waste by 2030, a reduction of 50% of N waste in Scottish agriculture would align with other examples. However, we recommend further research to determine a realistic N waste target for Scotland.

7.3.1. Research gaps for setting a N waste target

In the SNBS, N flows would need to be properly assigned to N waste and N re-use. Legumes would need to be included in the SNBS because N waste is likely to be lower than N input. A SMART target analysis for N waste would be beneficial to set a challenging and realistic target. It would be helpful to closer investigate the relationship between N waste and NUE targets if a NUE target is the long-term aim.

8. References

Antille, D. L., Moody, P. W. 2021. Nitrogen use efficiency calculators for the Australian cotton, grain, sugar, dairy and horticulture industries. Environmental and sustainability indicators, ELSEVIER.

Adaptation Scotland 2021 Climate Projections for Scotland Summary. https://www.adaptationscotland.org.uk/application/files/1316/3956/5418/LOW_RES_4656_Climate_Projections_report_SINGLE_PAGE_DEC21.pdf

Barnes, A., Bevan, K., Moxey, A., Grierson, S. and Toma, L., 2022. Greenhouse gas emissions from Scottish farming: an exploratory analysis of the Scottish Farm Business Survey and Agrecalc. Scotland's Rural College.

Brown, P., Cardenas, L., Choudrie, S., Del Vento, S., Karagianni, E., MacCarthy, J., Mullen, J., Passant, N., Richmond, B., Smith, H., Thistlethwaite, G., Thomson, A., Turtle, L. & Wakeling, D. (2021) UK Greenhouse Gas Inventory, 1990 to 2019. Ricardo Energy & Environment, Department for Business, Energy & Industrial Strategy, London quoted in Climate Exchange, 2023, Scenarios for emissions reduction targets in Scottish agriculture.

Duncombe, J. (2021). Index suggests that half of nitrogen applied to crops is lost, *Eos, 102*. https://doi.org/10.1029/2021EO162300.

Emmerling, C., Krein, A. and Junk, J., 2020. Meta-analysis of strategies to reduce NH3 emissions from slurries in European agriculture and consequences for greenhouse gas emissions. Agronomy, 10(11), p.1633. https://www.mdpi.com/867332

Eory, V., Topp, K., Rees, B., Jones, S., Waxenberg, K., Barnes, A., Smith, P., MacLeod, M. and Wall, E., 2023. A scenario-based approach to emissions reduction targets in Scottish agriculture. Scotland's Rural College. http://dx.doi.org/10.7488/era/3048

Eory, V., MacLeod, M., Topp, C.F.E., Rees, R.M., Webb, J., McVittie, A., Wall, E., Borthwick, F., Watson, C.A., Waterhouse, A. and Wiltshire, J., 2015. Review and update the UK agriculture MACC to assess the abatement potential for the 5th carbon budget period and to 2050: Final report submitted for the project contract "Provision of services to review and update the UK agriculture MACC and to assess abatement potential for the 5th carbon budget period and to 2050".

EU Nitrogen Expert Panel (2015) Nitrogen Use Efficiency (NUE) - an indicator for the utilization of nitrogen in agriculture and food systems. Wageningen University, Alterra, PO Box 47, NL-6700 Wageningen, Netherlands.

Germán Giner Santonja, Konstantinos Georgitzikis, Bianca Maria Scalet, Paolo Montobbio, Serge Roudier, Luis Delgado Sancho; *Best Available Techniques (BAT) Reference Document for the Intensive Rearing of Poultry or Pigs*; EUR 28674 EN; doi:10.2760/020485

Hawley, J., 2022. A comprehensive approach to Nitrogen in the UK.

Hellsten, S., Dalgaard, T., Rankinen, K., Tørseth, K., Bakken, L., Bechmann, M., Kulmala, A., Moldan, F., Olofsson, S., Piil, K. and Pira, K., 2019. Abating N in Nordic agriculture-Policy, measures and way forward. Journal of Environmental Management, 236, pp.674-686.

Houlton, B.Z., Almaraz, M., Aneja, V., Austin, A.T., Bai, E., Cassman, K.G., Compton, J.E., Davidson, E.A., Erisman, J.W., Galloway, J.N. and Gu, B., 2019. A world of cobenefits: solving the global nitrogen challenge. *Earth's future*, *7*(8), pp.865-872.

Jenkins, B., Avis, K., Willcocks, J., Martin, G., Wiltshire, J. and Peters, E., 2023. Adapting Scottish agriculture to a changing climate-assessing options for action. Ricardo Energy & Environment.

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J. 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ. Re. Lett.9. 111005.

Macgregor, C.J. and Warren, C.R., 2016. Evaluating the impacts of nitrate vulnerable zones on the environment and farmers' practices: a Scottish case study. *Scottish Geographical Journal*, *132*(1), pp.1-20.

McKay Fletcher, D., Ruiz, S., Williams, K., Petroselli, C., Walker, N., Chadwick, D., Jones, D.L. and Roose, T., 2022. Projected Increases in Precipitation Are Expected To Reduce Nitrogen Use Efficiency and Alter Optimal Fertilization Timings in Agriculture in the South East of England. ACS Es&t Engineering, 2(8), pp.1414-1424.

Munch, J.C. and Velthof, G.L., 2007. Denitrification and agriculture. In Biology of the nitrogen cycle (pp. 331-341). Elsevier.

Oenema, O., Bleeker, A., Braathen, N.A., Budňakova, M., Bull, K., Čermak, P., Geupel, M., Hicks, K., Hoft, R., Kozlova, N. and Leip, A., 2011. Nitrogen in current European policies. In The European nitrogen assessment (pp. 62-81).

Pozzer, A., Tsimpidi, A.P., Karydis, V.A., De Meij, A. and Lelieveld, J., 2017. Impact of agricultural emission reductions on fine-particulate matter and public health. Atmospheric Chemistry and Physics, 17(20), pp.12813-12826

Quemada, M., Lassaletta, L., Jensen, L. S., Godinot, O., Brentrup, F., Buckley, C., Foray, S., Hvid, S. K., Oenema, J., Richards, K. G., Oenema, O. 2020. Exploring nitrogen indicators of farm performance among farm types across several European case studies. ELSEVIER. Agricultural Systems, Vol 177. https://doi.org/10.1016/j.agsy.2019.102689

Rooke, J.A., Miller, G.A., Flockhart, J.F., McDowell, M.M. and MacLeod, M., 2016. Nutritional strategies to reduce enteric methane emissions.

Sanchez PA. 2002 Soil fertility and hunger in Africa. Science 295, 2019-20.

Sommer, S.G. and Knudsen, L., 2021. Impact of Danish livestock and manure management regulations on nitrogen pollution, crop production, and economy. Frontiers in Sustainability, 2, p.65823

Sutton, M.A., Howard, C.M., Kanter, D.R., Lassaletta, L., Móring, A., Raghuram, N., Read, N., 2021. The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond. Elsevier. *One Earth* Volume 4, Issue 1, p10-14. https://doi.org/10.1016/j.oneear.2020.12.016

Sutton, M.A., Skiba, U.M., Van Grinsven, H.J., Oenema, O., Watson, C.J., Williams, J., Hellums, D.T., Maas, R., Gyldenkaerne, S., Pathak, H. and Winiwarter, W., 2014. Green economy thinking and the control of nitrous oxide emissions. *Environmental Development*, *9*, pp.76-85.

Udvardi, M., Below, F.E., Castellano, M.J., Eagle, A.J., Giller, K.E., Ladha, J.K., Liu, X., Maaz, T.M., Nova-Franco, B., Raghuram, N. and Robertson, G.P., 2021. A research road map for responsible use of agricultural nitrogen. Frontiers in Sustainable Food Systems, 5, p.660155

United Nations Environment Programme, Global Partnership on Nutrient Management, & International Nitrogen Initiative (2013). Our Nutrient World: The Challenge to Produce More Food and Energy with Less Pollution. https://wedocs.unep.org/20.500.11822/10747.

Van Grinsven, H. J. H., ten Berge, H. F. M., Dalgaard, T., Fraters, B., Durand, P., Hart, A., Hofman, G., Jaconsen, B. H., Lalor, S. T. J., Lesschen, J. P., Osterburg, B., Richards, K. G., Techen, A. K., Vertes, F., Webb, J., Willems, W. J. 2012. Management, regulation and environmental impacts of nitrogen fertilization in northwestern Europe under Nitrates Directive; a benchmark study. Article, Vol. 9. Issue 12. 5143-5160.

Waqas, M., Hawkesford, M.J., Geilfus, C.M. 2023. Feeding the world sustainably: efficient nitrogen use. Trends in Plant Science. Volume 28, Issue 5. Pages 505-508. https://doi.org/10.1016/j.tplants.2023.02.010.

9. Appendix / Appendices

9.1. Appendix A: Nitrogen and its relevance to agriculture

Leaching and the effects on eutrophication

Leaching is the loss of N (as nitrate) as water drains through the soil moving nitrate away from the root zone. Both organic forms of N (such as slurry and manures) and inorganic fertilisers are liable to leaching. When nitrate is leached from soils, it can enter watercourses contributing to environmental problems such as eutrophication. Eutrophication is an accumulation of nutrients in watercourses causing excessive plant and algal growth resulting in reduced water quality and impacts upon fish, invertebrates and plant diversity. The extent of leaching is determined by factors such as soil type, crop cover, land management methods, geological characteristics and meteorological conditions prior to, during and following the application of the nutrients.

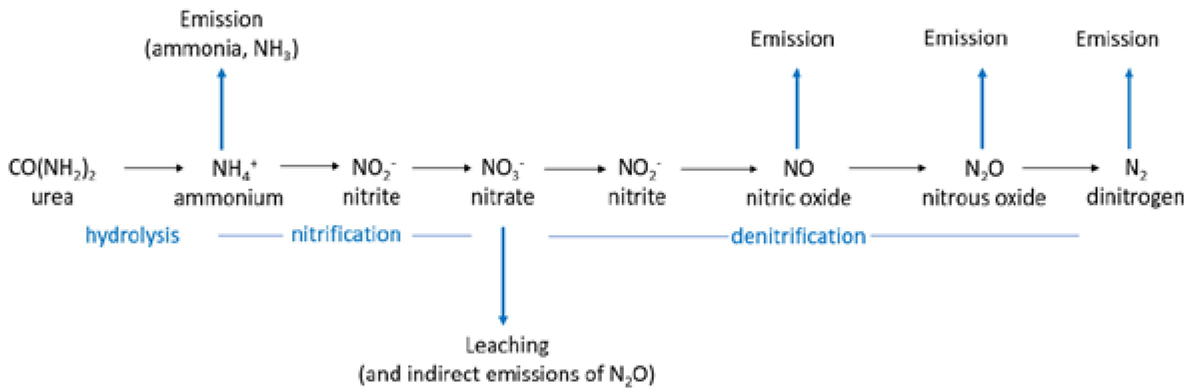
How NH_3 is emitted from agricultural sources

Loss of ammonia which is a significant air pollutant impacting upon both human health and biodiversity (respiratory harms and nutrient enrichment of sensitive habitats) is common from agricultural systems. Ammonia is lost through volatilisation of ammonium (NH_4+).

How N_2O is emitted from agricultural sources

Nitrous oxide is emitted in the process of denitrification, a bacterial process in waterlogged soils that converts nitrate to nitrous oxide and N_2 (for more explanation regarding the chemical processes involved please see Annex F). N_2O is a potent greenhouse gas and forms a significant contribution to agriculture's impact on climate warming.

9.2. Appendix B: Chemical processes of Nitrogen



9.3. Appendix C: Rapid evidence assessment methodology

The Rapid Evidence Assessment (REA) methodology used for this project aligns with NERC methodology and comprised of the following steps.

1. **Define the search strategy protocol, identify key search words or terms, define inclusion/exclusion criteria.** A list of key words, terms and search strings were created and reviewed by the project steering group to direct the REA review to the most relevant sources.
2. **Searching for evidence and recording findings.** Literature was searched using Google Scholar, utilising our accounts with Science Direct and Research Gate to access restricted PDF's where required. When searching through Government websites (to find policy initiatives and associated targets), the search engine Google was used. Searches were divided into academic literature and government websites (including farming press and industry). A unique search reference was assigned for each individual search, and the date, search string used, total number of results found, and the total number of relevant papers found were recorded. Examples of search strings include:
    a. "Nitrogen" "target" "Europe"
    b. NH_3 target agriculture
    c. Nitrate leaching target
    d. Emission reduction target Denmark

All results were recorded in an excel spreadsheet with information extracted on the following:

a. Country
b. Target
c. Target timeframe
d. Benefits and risks/challenges of proposed target
e. Mitigation measures (introduced, planned and proposed/suggested)

A RAG (red, amber, green) rating was also assigned for each source, based on the following criteria:

Description	Rating
Quality	
Peer reviewed journal, sound data sources and methodology	Green
Government funded research reports, sound data sources and methodology	Green
International Nitrogen Management System (INMS)	Green
Research funded by NGOs (e.g. AHDB), sound data sources and methodology	Amber

Work is unreliable because of unreliable data sources, or limited sources, or because the method is not robust	Red
Information from websites, blogs etc., of unknown quality	Red
Relevance	
Timeframe: within last 10 years	Green
Timeframe: within last 20 years	Amber
Timeframe: older than 20 years	Red

3. **Screening.** Sources of evidence were then screened initially by title and then accepted papers were screened again using the summary or abstract. Literature was screened for information on the following inclusion criteria:
   a. Nitrogen target (including but not limited to target for NUE or nitrogen emissions, or nitrogen fertiliser use, or nitrogen deposition)
   b. Benefits and risks of introducing a target
   c. Mitigation methods that improve NUE, or decrease nitrogen inputs
4. **Extract and appraise the evidence.** The screening provided an organised list of papers which enabled evidence to be extracted directly from the literature into the report. Literature extracted also guided the internal workshop and supported information included in the SWOT and PESTLE tables**.**

How was the evidence found used. Evidence gathered from the REA was used to identify the different types of N targets used in other countries and provided a discussion following examples of the relevance of these targets to Scottish agriculture (section 4). The evidence was also used to identify the benefits and risks of setting a NUE target for Scotland and assisted the SWOT and PESTLE analysis (section 5) and to inform criteria and underpin recommendations for setting an appropriate target/s for Scotland.

9.4. Appendix D: Country-specific changes (%) in NUE values from 1961 to 2014

Table 6: Country-specific changes (%) in NUE values from 1961 to 2014 (Our World in Data)

Country or region	Year		Relative change (%)
	1961 (%)	2014 (%)	
Denmark	39.68	74.29	87
Finland	34.51	57.08	65
France	37.89	73.87	95
Germany	37.71	62.62	97
Greece	65.22	50.25	11
Hungary	45.26	92.95	105
Iceland	0.38	0.21	43
India	43.73	34.34	21
Indonesia	48.2	80.38	67
Ireland	77.02	86.9	13
Italy	47.85	52.64	10
Japan	37.36	27.87	25
Latvia	58.75	61.41	5
Luxembourg	49.71	18.29	63
Malaysia	42.81	262.09	512
Mexico	75.78	45.74	40
Netherlands	18.15	37.1	104
New Zealand	10.26	5.23	49
North Korea	49.68	41.85	16
Norway	20.08	20.35	1
Poland	48.16	45.27	6
Portugal	33.39	19.2	42
Romania	40.8	107.17	163
Russia	64.37	125.2	95
Sweden	43.15	53.01	23
Switzerland	50.53	36.66	27
UK	28.36	66.69	135
USA	71.9	71.61	0

9.5. Appendix E: Analysis & recommendation development Methodology

1. Data collection

Relevant measures were collated from results of the REA. The impact factors for these measures on N flows was extracted into an excel file.

2. Data extraction

All relevant data points were extracted from the papers into an Excel spreadsheet manually.

3. Data appraisal

A RAG rating was applied to all data sources based on the quality of the data (including publishing date, assumptions made, applicability etc.). Where data was considered to be very poor quality, alternative sources to fill or improve this data point were sourced.

4. Mapping

Relevant mitigation measures were mapped on to the SNBS according to what nitrogen flows they impacted. This allowed for accurate modelling of the change in nitrogen flow, and subsequently nitrogen use efficiency, if the measures are implemented at the estimated uptake rates in the given years.

5. Calculations

Once the impact values had been mapped on to relevant N flows, they were evaluated to ensure that the theory behind these values relate and can therefore be applied to the values in the SNBS. This involved ensuring that each measure had a relative impact value as percentage, and that the baseline is applicable to that in the SNBS.

Applicability: the portion of the relevant flow in the SNBS that the measure/impact value applies to e.g. emissions from livestock are grouped in one flow in the SNBS, and so a measure/impact value relevant to only dairy animals can only be applied to a portion of the N flow value. There were several sources used to determine this granularity of application. For livestock sectors the Scottish agricultural census data was used. The total livestock number in heads was divided by the total number of livestock from all sectors and reported as a percentage. Fertiliser use was determined from data within the Agricultural SMT produced by ADAS.

Some measures that include N fixation may not improve NUE but will reduce mineral N inputs.

Current uptake: An estimation of the portion of the relevant N flow that is subject to the impact of the measures. This is subtracted from the overall applicability as the impact is already considered in the current NUE values. In this way double counting of impacts is avoided.

Maximum future impact: Calculated as applicability minus current uptake, multiplied by the impact value. This calculates the impact the measure may have if implemented on all remaining applicable units. The value is then multiplied by the projected future uptake value in each of the time points to produce an estimate for the impact that could be expected.

6. Quality Assessment

All data inputs, calculations, and outputs of this task were reviewed internally by the sector experts to ensure robustness and validity. Where possible the results were also compared to peer reviewed literature to ensure that they were consistent with the current scientific understanding.

7. Assumptions around SNBS

There is no flow that relates to N from soil into grass, so impacts on this could not be quantified in the SNBS.

Crop residue N is recycled within the system. Therefore, this flow is not considered in the NUE calculations in the SNBS, and so any impacts to crop residue N due to implementation of measures will not be reflected in an improvement to NUE. To compensate for this, improvements to crop residue N was modelled as a reduction in N inputs from fertilisers.

There is around 30kt N unaccounted for through livestock flows. This is perhaps accounted for in what is considered in the report as 'stocks' – i.e. an amount of N in living livestock at any one time.

9.6. Appendix F: Description of measures and assumptions

In the following tables, where the source is given as “other CXC paper” this is referring to the paper Eory, V., et al. (2023) and “MACC Update” refers to the paper Eory V., et al. (2015).

1. Preventing soil compaction

Approximately 20% of arable land in Scotland is susceptible to soil compaction and is therefore eligible to have compaction prevention applied. This measure is expected to increase yields and crop residue N, and so is assumed to reduce mineral N requirements.

Paper	CXC	CXC	CXC	CXC	CXC	CXC
Sector	Arable	Grassland	Arable	Grassland	Arable	Grassland
N Effect	Crop Residue N	Crop Residue N	Yield	Yield	N_2O Emission Factor	N_2O Emission Factor
Value	2%	1%	2%	1%	-6%	-6%
Applicability	20.00%	20.00%	20.00%	20.00%	20.00%	20.00%
Current Uptake	0%	0%	0%	0%	0%	0%
Maximum Future Impact	2.00%	1.00%	2.00%	1.00%	-6.00%	-6.00%
Uptake 2030	1%	1%	1%	1%	1%	1%
Uptake 2040	2%	2%	2%	2%	2%	2%
uptake 2045	2%	2%	2%	2%	2%	2%
2030	-0.01%	-0.01%	-0.01%	-0.01%	-0.04%	-0.04%
2040	-0.03%	-0.02%	-0.03%	-0.02%	-0.10%	-0.10%
2045	-0.04%	-0.02%	-0.04%	-0.02%	-0.13%	-0.13%

2. Optimal soil pH

This measure involves applying lime to soils to ensure that soil pH is in the optimal range for N availability. This means that when applying N fertilisers there will be less excess N as it will be more bioavailable and taken up by crops. This has been found to increase crop residue N and yield, both by 6%, while reducing the emission of N_2O by 3%, in arable and grassland. It has previously been assumed that approximately 9% of arable land and 22% grassland are applicable to have pH optimised**Error! Bookmark not defined.**.

Paper	CXC	CXC	CXC	CXC	CXC	CXC
Sector	Arable	Grassland	Arable	Grassland	Arable	Grassland
Nitrogen Effect	Crop Residue N	Crop Residue N	Yield	Yield	N2O Emission Factor	N2O Emission Factor
Value	6%	6%	6%	6%	-3%	-3%
Applicability	9.00%	22.00%	9.00%	22.00%	9.00%	22.00%

Current Uptake	0%	0%	0%	0%	0%	0%
Maximum Impact in Future	-0.56%	-1.37%	0.56%	1.37%	-0.27%	-0.66%
2030	-0.17%	-0.41%	0.17%	0.41%	-0.08%	-0.20%
2040	-0.22%	-0.55%	0.22%	0.55%	-0.11%	-0.26%
2045	-0.42%	-1.03%	0.42%	1.03%	-0.20%	-0.50%
Uptake 2030	30%	30%	30%	30%	30%	30%
Uptake 2040	40%	40%	40%	40%	40%	40%
uptake 2045	75%	75%	75%	75%	75%	75%

3. Use of catch/cover crops

Catch/cover crops are non-productive plants cultivated between catch crops with the effect of taking up excess N that was left in soil, having not been taken up by the preceding cash crop. This reduces the amount of N (in the form of NO_3^-) that is lost in leaching by 45%. The applicability of this measure to crops has previously been set to 34%.

Paper	MACC Update
Sector	
Nitrogen Effect	Frac_Leach
Value	-45%
Applicability	34.00%
Current Uptake	30.00%
Maximum Future Impact	-10.71%
2030	-0.75%
2040	-1.82%
2045	-2.36%
Uptake 2030	7%
Uptake 2040	17%
uptake 2045	22%

4. Variable rate nitrogen application

Variable rate nitrogen application (VRNT) is where a digital map or real-time sensors supports a decision tool that calculates the N needs of the plants, transfers the information to a controller, which adjusts the spreading rate (Barnes *et al.* 2017). This measure is applicable to all land that receives fertiliser. 2-22% of farms use precision farming technologies and 16% used variable rate application, though only 11% use yield mapping (25% cereal farms, 18% other crop farms, 5% pig/poultry and dairy farms, 2% grazing livestock farms, 11% mixed farms). This measure can increase yield, reduce fertiliser use rates, and increase crop residue N. As with all measures yield is kept constant with current levels, and crop residue N is considered through a decrease in N fertilisation. Therefore, this measure is modelled as a decrease to N inputs through three mechanisms.

Paper	CXC	CXC	CXC	CXC	CXC	CXC
Sector	Crop	Grassland	Crop	Grassland	Crop	Grassland
Nitrogen Effect	N fertilisation rate	N fertilisation rate	Crop yield	Crop yield	Crop residue N	Crop residue N
Value	-5%	-5%	-3%	-3%	-3%	-3%
Applicability	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Current Uptake	21.50%	2.00%	21.50%	2.00%	21.50%	2.00%
Maximum Impact in Future	-3.93%	-4.90%	-2.36%	-2.94%	-2.36%	-2.94%
2030	-0.27%	-0.34%	-0.16%	-0.21%	-0.16%	-0.21%
2040	-0.67%	-0.83%	-0.40%	-0.50%	-0.40%	-0.50%
2045	-0.86%	-1.08%	-0.52%	-0.65%	-0.52%	-0.65%
Uptake 2030	7%	7%	7%	7%	7%	7%
Uptake 2040	17%	17%	17%	17%	17%	17%
uptake 2045	22%	22%	22%	22%	22%	22%

5. Urease Inhibitors

Urease inhibitors slow down the hydrolysis of urea to ammonia when urea-based fertilisers are applied to soils, reducing ammonia emissions and increasing the N available to plants.

Paper	CXC	CXC	CXC
Sector	Crop	Crop	Crop
Nitrogen Effect	N2O Emission Factor	N leaching	N fertilisation rate
Value	-27%	-13%	-17%
Applicability	8.40%	8.40%	8.40%
Current Uptake	0.00%	0.00%	0.00%
Maximum Impact in Future	-2.27%	-1.10%	-1.41%
2030	-0.56%	-0.27%	-0.35%
2040	-1.35%	-0.65%	-0.84%
2045	-1.75%	-0.85%	-1.09%
Uptake 2030	25%	25%	25%
Uptake 2040	60%	60%	60%
uptake 2045	77%	77%	77%

6. Nitrification Inhibitor

Paper	CXC	CXC
Sector	Crop	Crop
Nitrogen Effect	N2O Emission Factor	N2O Emission Factor
Value	-60%	-30%
Applicability	7.50%	36.50%
Current Uptake	0.00%	0.00%
Maximum Impact in Future	-4.50%	-10.95%
2030	-0.53%	-1.28%
2040	-1.27%	-3.10%
2045	-1.65%	-4.02%
Uptake 2030	12%	12%
Uptake 2040	28%	28%
uptake 2045	37%	37%

7. Improved Nutrition

Improving the nutrition of livestock can involve matching N in feed to the needs of the animal, improving the availability of N in the feed to animal, improving the digestibility of the feed so that more N is utilised by the animal and converted to liveweight. This can reduce N inputs and/or reduce N losses while keeping useful N outputs constant, and so increases NUE. From previous modelling of this measure in Scotland it was found that the N content of feed could be reduced by 2% in beef, poultry, and dairy, while excreted N could be reduced by 5% in pigs and 2% in sheep. The applicability of this measure for each livestock type is based on the proportion of total livestock units of each livestock type based off the Scottish Agricultural Census. The current uptake is based off data from previous reports modelling this measure in Scotland.

Paper	CXC	MACC (2020)	MACC (2020)	MACC (2020)	CXC
Sector	Beef	Pigs	Poultry	Dairy	Sheep
Nitrogen Effect	Feed	N Excreted	Feed	Feed	N excreted
Value	2%	5%	2%	2%	-2%
Applicability	42.46%	11.50%	10.35%	10.84%	23.03%
Current Uptake	20.00%	80.00%	80.00%	80.00%	20.00%
Maximum Impact in Future	0.68%	0.12%	0.04%	0.04%	-0.37%
2030	0.08%	0.01%	0.00%	0.01%	-0.04%
2040	0.19%	0.03%	0.01%	0.01%	-0.10%
2045	0.25%	0.04%	0.02%	0.02%	-0.14%
Uptake 2030	12%	12%	12%	12%	12%
Uptake 2040	28%	28%	28%	28%	28%
uptake 2045	37%	37%	37%	37%	37%

8. Improved health

This measure includes eliminating issues including worms, liver fluke, and lameness, increasing the productivity/efficiency of the animals. While in theory 100% of the herd could have improved health (the stance taken in CXC A scenario), an 80% applicability value was chosen, following the assumption in CXC marginal abatement. This will produce a slightly more conservative estimate of the impact on NUE, to allow for not all diseases/health issues that contribute to lower productivity being treatable/eradicated, and a portion of the herd that may already be achieving higher health. Previous studies focusing on improving livestock health to mitigate nutrient loss, greenhouse gas loss etc. focused on the mechanism of increased productivity. Therefore, as we are keeping yields constant in this model the increased productivity is factored in as a reduction in feed inputs.

Paper	CXC	CXC	CXC
Sector	Dairy	Beef	Sheep
Nitrogen Effect	Milk Yield	Liveweight	Liveweight
Value	6%	6%	10%
Applicability	41.63%	24.05%	8.21%
Current Uptake	0.00%	0.00%	0.00%
Maximum Future Impact	2.66%	1.53%	0.86%
2030	0.80%	0.46%	0.26%
2040	1.50%	0.87%	0.49%
2045	1.95%	1.13%	0.63%
Uptake 2030	30%	30%	30%
Uptake 2040	57%	57%	57%
uptake 2045	73%	73%	73%

•

9. Livestock Genetics

Livestock genetics techniques can be used with various goals including increasing productivity, climate resilience, or reducing emissions. For improving NUE of livestock systems the key goal is increasing efficiency i.e. increasing the utilisation of N and yield of livestock products, compared to the feed N intake levels. The uptake of using better genetic material is only around 20-25% in the dairy herd, and still lower in the beef herd (Defra 2018). The outcomes of this measure will depend on the breeding tools used and the breeding goal chosen. Three more specific measures have been gathered from the literature, and their potential impact on NUE has been modelled. These are:

- Increased uptake of the current approach in the dairy herd,
- Using the current breeding goals but enhancing the selection process by using genomic tools, in dairy and beef,
- New breeding goals to include lower GHG emissions, using genomic tools.

In 2018 usage of improved genetic material was reported as 20-25% in the dairy herd, and less in the beef herd. However, several previous projects modelling similar measures set the current uptake at 0% of both dairy and beef herds.

Paper	CXC	CXC	CXC
Sector	Dairy	Dairy	Beef
Nitrogen Effect	Milk yield	Milk protein	Liveweight
Value	1%	1%	0%
Applicability	10.84%	10.84%	42.46%
Current Uptake	60.00%	60.00%	25.00%
Maximum Future Impact	0.04%	0.04%	0.08%
Uptake 2030	15%	15%	5%
Uptake 2040	25%	25%	10%
uptake 2045	35%	35%	20%
2030	0.00%	0.00%	0.00%
2040	0.00%	0.00%	0.00%
2045	-0.01%	-0.01%	-0.03%

10. Slurry acidification

Livestock excreta is susceptible to N volatilization, leading to losses to the atmosphere using storage, and leaching during spreading. Acidification of slurry can immobilize the N and reduce these losses. The impact of acidification is largely measured and reported in reductions to emissions, however, as the emissions values are not considered in the NUE calculations this has to be transformed to an impact on inputs. Higher N in slurry will increase yields/maintain yields with lower inputs. Therefore, in this model we include the impact of slurry acidification as a reduced input of N to land receiving fertiliser.

Paper	CXC	CXC	CXC	MACC Update	MACC Update	MACC Update
Sector	Dairy	Beef	Pigs	Dairy	Beef	Pigs
Nitrogen Effect	NH3 Volatilisation	NH3 Volatilisation	NH3 Volatilisation	N2O Emission	N2O Emission	N2O Emission
Value	-75%	-75%	-75%	-23%	-23%	-23%
Applicability	2.28%	0.85%	2.19%	2.28%	0.85%	2.19%
Current Uptake	0.00%	0.00%	0.00%			
Maximum Future Impact	-1.71%	-0.64%	-1.64%	-0.52%	-0.20%	-0.50%
Uptake 2030	7%	7%	7%	7%	7%	7%
Uptake 2040	17%	17%	17%	17%	17%	17%
uptake 2045	22%	22%	22%	22%	22%	22%
2030	-0.12%	-0.04%	-0.11%	-0.04%	-0.01%	-0.04%
2040	-0.29%	-0.11%	-0.28%	-0.09%	-0.03%	-0.09%
2045	-0.38%	-0.14%	-0.36%	-0.12%	-0.04%	-0.11%

11. Slurry store cover

Based on an impermeable slurry cover. Impact and uptake values taken from previous CXC paper. The flow in the SNBS does not distinguish between NH_3 emissions from housing and spreading and N_2O emissions from animal husbandry in general. The portion of each of these gaseous emissions was then extrapolated from the SMT. An impermeable cover is applicable to 100% of slurry tanks and lagoons as there is no available uptake data.

Paper	CXC	CXC	CXC	CXC	CXC	CXC
Sector	Dairy	Dairy	Beef	Beef	Pigs	Pigs
Nitrogen Effect	NH3 Volatilisation	N2O Emission	NH3 Volatilisation	N2O Emission	NH3 Volatilisation	N2O Emission
Value	-80%	-100%	-80%	-100%	-80%	-100%
Applicability	6.25%	2.71%	0.85%	0.85%	4.26%	4.26%
Current Uptake	0.00%	0.00%	0.00%	0.00%	24.00%	24.00%
Maximum Future Impact	-5.00%	-2.71%	-0.68%	-0.85%	-2.59%	-3.23%
Uptake 2030	18%	18%	18%	18%	18%	18%
Uptake 2040	43%	43%	43%	43%	43%	43%
uptake 2045	55%	55%	55%	55%	55%	55%
2030	-0.88%	-0.47%	-0.12%	-0.15%	-0.45%	-0.57%
2040	-2.13%	-1.15%	-0.29%	-0.36%	-1.10%	-1.37%
2045	-2.75%	-1.49%	-0.37%	-0.47%	-1.42%	-1.78%

12. Low Emission Housing

Acid air scrubbers can remove nitrogen from air, reducing NH3 emissions, which can then be applied to soils as N fertiliser, and essentially recovering more N in useful outputs by reducing waste N in emissions. Approximately 90% of recovered N can be reinput into the soil. The removal efficiency depends on the specific machinery used and approximately 90% can be expected for acid air scrubbers.

Paper	Comparing environmental impact of air scrubbers for ammonia abatement at pig houses: A life cycle assessment (sciencedirectassets.com)	Comparing environmental impact of air scrubbers for ammonia abatement at pig houses: A life cycle assessment (sciencedirectassets.com)
Sector	Pigs	Poultry
Nitrogen Effect	Recovering emissions	Recovering emissions
Value	-81%	-81%
Applicability	12%	10%
Current Uptake		
Maximum Impact in Future	-9.32%	-8.38%
Uptake 2030	7%	7%
Uptake 2040	17%	17%
uptake 2045	22%	22%
2030	-0.65%	-0.59%
2040	-1.58%	-1.42%
2045	-2.05%	-1.84%

13. Novel Crops

Novel crops (crops with improved NUE) is designed to reflect the impact of growing new cultivars of crops that can maintain (or improve yields) with a lower requirement for N inputs as fertiliser. Previous

Paper	MACC Update
Sector	Arable
Nitrogen Effect	N fertilisation rate
Value	-9%
Applicability	70.00%
Current Uptake	0.00%
Maximum Impact in Future	-6.30%
2030	-13.23%
2040	-2.52%
2045	-4.73%
Uptake 2030	30%
Uptake 2040	40%
uptake 2045	75%

14. Rapid Incorporation

Paper	SMT
Sector	
Nitrogen Effect	NH3 Volatilisation
Value	-41%
Applicability	100%
Current Uptake	26%
Maximum Impact in Future	-30.34%
Uptake 2030	12%
Uptake 2040	28%
uptake 2045	37%
2030	-9.10%
2040	-8.60%
2045	-11.12%

15. General Assumptions:

- Take the total inputs and subtract the total loss to atmosphere as NH_3 and loss to run off and leaching
- Maybe assume that N_2 and NOx stay constant, NH_3 and N_2O, estimate the losses and subtract from inputs
- Ignore crop residue N, check how this impacts flow
- Increased N fixation will lead to reduced mineral fertiliser inputs, balance out

- Reduced losses (N_2O, NH_3, leaching) will reduce inputs in equal amounts (may need to apply a percentage to this, as farmers may only reduce inputs by 80%, may have to look into the literature)
- Maintain yield (useful outputs), and so any change to output will be modelled as a change to inputs. This is based on the principle that there will be economic drivers at play that will mean on a Scotland wide scale production levels will be maintained, and so if there is a yield increase/decrease on one farm this will be balanced out by the converse on a different farm. Any yield increase/decrease will be felt as the converse in inputs – feed, fertiliser etc. will be reduced in line with the estimated increase of milk, liveweight, crop, etc.
- All legume measures will not impact NUE as any saving in N fertilisation will be balanced by increased biological fixation.
- Assumed that legumes are included once in every five years. Therefore, a fertiliser saving is felt in two of every five years and so impacts 40% of the mineral fertiliser input to crops flow (one year (20%) will be saved from the legume cycle, and one year (20%) from the subsequent crop year due to residual soil N).
- Within the SNBS, nitrogen flows to or from livestock pools were given as a single value for all livestock, rather than by type. However, the measures relating to livestock were species-specific (e.g. slurry acidification in dairy slurry and pig slurry). To compensate for this the number of heads of each livestock type (from the Scottish agricultural census) was converted to livestock units, and then the proportion of total livestock amount of each type was calculated and applied to the relevant measures.
- A single flow value is provided in the SNBS for all mineral fertiliser to crops and all mineral fertilisers to grass, however several of the measures only impact a certain type of fertiliser or may have a different impact depending on the type of fertiliser.

9.7. Appendix G: SWOT and PESTLE Analysis

The risks and benefits to Scotland from determining a NUE target were determined through giving consideration to numerous avenues of information and data. Evidence gathered following the completion of Task 1 (evidence review) focusing upon risks and benefits of setting NUE targets in other countries were collated and analysed. This was followed by an internal workshop, led by key experts within the agricultural field, to determine the applicability of the information to Scotland, during which time additional risks and benefits were identified. Following the internal Workshop, a more detailed study of the aspirations and trends in agricultural practices set by the Scottish Government was undertaken. The SWOT (strengths, weaknesses, opportunities, threats) and PESTLE (political, economic, sociological, technological, legal and environmental) tables were populated to better understand the complexities of the information gathered by Ricardo, with the analysis tools providing a summary of the risks and benefits of setting a NUE target in Scotland and demonstrating how a range of influences can support or hinder the achievement of a NUE target. The points presented in both the SWOT and PESTLE analysis have varying degrees of severity therefore a judgment on overall supporting and hindering influences cannot be made on the number of points alone.

SWOT

Strengths, weaknesses, opportunities, and threats (SWOT) of setting N-related targets were analysed based on the information gathered on N targets in other countries. We also included analysis of GHG and climate related targets where relevant to increase the body of information. This information was then used to assess applicability of setting a NUE target for Scottish agriculture with the limitation that the analysis was based on N, GHG and climate related rather than NUE specific targets. The SWOT analysis shows a range of influences which can support or hinder the achievement of a NUE target.

	Strengths of a NUE target	Weaknesses of a NUE target
Internal	• **Raises awareness** of the contribution of N use to GHG emissions • **Mid-point assessments** allow long-term benefits of N deposition reduction to be communicated on political timescales • Regulation has a strong impact on land-management decisions • Targets are **meaningful reference values** which convey a desired outcome • Various **treaties and regulations have put limits or targets on N use**; information is available in terms of reducing N pollution (e.g., NVZ) • Technologies and measures that can support the success of a NUE target already exist and continue to be developed • **Data** on attainable NUE exists in literature • Supports fertiliser efficiency, reducing imported input demand • Many mitigation measures are relatively low cost and accessible • NUE can be estimated at different **spatial and temporal scales** • Improvements in NUE are **achievable** • A **voluntary approach** may attract more farmer involvement • Can support a NUE **indicator for** the food system including food waste, transport, exports etc , supporting wider national policies • **Support farm profitability** by reducing spend on inputs • **Work is ongoing to increase the data availability** for GHG mitigation potential, and the economic costs and benefits of mitigation measures	• **Some government funding is needed,** for example, to help cover large upfront investments for some measures e.g. low emission spreading machinery • Enforcing measures requires **political will** that may be in tension with the current rhetoric around food security. • Some mitigation measures may need to be repeated or changed frequently which requires monitoring (e.g. nitrification inhibitors need to be used annually) • There is **no single universally applicable path** for increasing NUE which can reduce action due to confusion on what to do • To set a target, accurate current uptake levels for relevant measures need to be known (high current uptakes limit the potential for further improvements to NUE), which is not currently the case. Some measures may already be in widespread use, which limits **the potential for additional reductions.** • A target with a voluntary approach may limit success and require 'buy-in' from farmers • **Biogeochemical hysteresis effects** are not yet well understood quantitatively (Being able to quantify the indirect effects of introducing new mitigation measures (e.g., change of N management) on the wider ecosystem (e.g., N cycle) are not well understood). • **Predicting future uptake levels** for mitigation measures is difficult • Improving NUE reduces emissions of N, but does not eliminate them, so there is **target limitation** • Some measures that are good for N use (e.g., legume crops) may **not be reflected in the SNBS** • A clear, nationwide strategy to support farmers in **implementing measures on a broad scale to improve NUE on farm** is currently lacking

	O Opportunities presented by having a NUE target	Threats presented by having a NUE target

External	• The SNBS will allow annual **monitoring**
	• To date, **progress has been small** in reducing nutrient pollution and N emissions from agricultural sources, improvements in NUE offer opportunities to significantly reduce N emissions without significantly disproportionate costs to the agricultural sector
	• Drive better practices on farm
	• Binding targets can deliver high reductions in N losses and encourage farmers beyond mitigation and into prevention
	• Supports effective and efficient policy
	• **Proposing multiple mitigation measures** suited to different farming types can increase uptake
	• Learn from other policy initiatives e.g. The Colombo Declaration
	• Further promote the **development of technologies and measures** that support better N use
	• **Farm support programs** for purchase/modernisation of agricultural equipment
	• Farmers can use N **modelling tools** to assess the effectiveness of different mitigation measures
	• **Build upon the sector's work** to increase adoption of region and farm-specific measures
	• Training can be far-reaching and can be combined with incentives and verification at all stages
	• **Private markets** could pay farmers to adopt practices that produce ecosystem services
	• Knock on benefits of better NUE include
	    o Reduction of other pollutants e.g., GHGs, NH3
		• Binding N targets have led to **civil unrest** in other countries so potentially**, government enforcement of a target (i.e. introducing a tax)** may cause civil unrest
		• A voluntary approach with further reductions in limits may result in less buy-in from farmers
		• **'Overly' ambitious targets** may drive farmers out of business with community implications
		• Unintended consequences e.g., pollution swapping
		• Even if measures are as successful as anticipated and are fully adopted, the cumulative **reduction may be less than the estimated potential**
		• **Setting an unambitious/low target** could be seen as a "parody which pushes responsibility onto other sectors"
		• **'Quick-win' results** may hinder future development
		• Implementation of mitigation measures may need monitoring and enforcement
		• Biogeochemical hysteresis effects
		• Mitigation measures **may interfere with other regulations** e.g., land-use regulation
		• Challenging to change animal **production technology**, change **agrotechnics** and progress **technological and digital transformation** to support the success of a NUE target
		•
		Threats to achieving a NUE target
		    • **Climate change** affects the sources and sinks of N
		• Legislative delays
		• Incorrect implementation of measures

	○ Improvement of water quality ○ Improvements to air quality ○ Improvements to human health ○ Biodiversity benefits ○ Saves farmers' money	

PESTLE

Setting NUE and other N targets are subject to a range of enablers and barriers. Therefore, a political, economic, social, technical, legal, and environmental (PESTLE) analysis was undertaken to assess the feasibility of setting a NUE target for Scottish agriculture, again, with the limitation that the analysis was based on N, GHG and climate related rather than NUE specific targets. The PESTLE assessment took place following the SWOT analysis to ensure the findings from the SWOT were assessed and, if relevant, included into the PESTLE categories.

	Enablers	Barriers
Political	• Socioeconomic, cultural and health considerations can be used to inform policies. In the context of N this includes impacts on air and water pollution, climate, farmer incomes and biodiversity. • The introduction of government policy incentivises uptake of mitigation measures by providing focus and direction • NUE increase is complimentary with other economic, environmental, health and climate policy objectives • **Regulatory instruments** (pollution standards and ceilings/fertiliser use limits/ BAT)	• Negative experiences in other countries who are dealing with a similar challenge (E.g., farmer protests following the Dutch government proposals to tackle N emissions) • Lack of clarity on synergies with other policies • Pushback on measures seen to reduce productive output in terms of food production

Economic	• Optimal use of fertiliser saving farmer's money • Capital grants or support schemes can help shoulder on-farm costs and encourage uptake of the more expensive mitigation measures (e.g. specialised spreading equipment) • Mitigation measures are expected to span a wide range of activities and may result in net benefits to farmers (e.g., improvement in farm profitability) • Many mitigation measures are low cost and available to farmers • Policy levers available to encourage optimal use of fertiliser	• Lack of incentives • Mitigation measures are expected to span a wide range of activities and may result in net costs to farmers • Upfront investments required to implement some new technologies and strategies to reduce emissions • Recurring costs of mitigation measures
Social	• Health benefits e.g., controlling N pollution will lower nitrate concentrations in drinking water • Public drive and increasing interest in climate, health and environment can influence policy (increasing interest from public) • Increase in value of farm produce • Current lower levels of **fertiliser use** (due to high prices) can complement a NUE target and contribute to an ambitious target • **Communicative instruments** (extension services/ education, awareness and persuasion/ co-operative approaches)	• A target with a non-mandatory approach will require buy-in from farmers • Potential impact on output if N is changed without proper strategies in place e.g. removing all fertiliser use (reduced yields/switching effect due to challenges of continuing to produce products profitably) • Perception of potential for decreased yield/ production security

Technical	• Technology and measures exist to improve NUE, and solutions continue to be developed through research • The SNBS annually monitors and measures Scottish agriculture's NUE • Training and advice to farmers, feed companies and other support services would support NUE increases	• Many farmers are not aware of why and how to improve N use • Monitoring and measuring NUE target success at sub-sector level (i.e. for different farming systems) is not currently possible at a central level
Legal	• Legislation to support a NUE target exists e.g., Cleaner Air for Scotland Strategy Plan 2021, Scotland's Agricultural Reform Route Map • The objectives of existing legislation would be supported (air and water quality, farmer incomes, biodiversity and human health)	• Farmers may not comply with regulatory requirements • A NUE target must fit in with other environmental legislation (e.g., integrate with The N directive, National Emissions Ceiling Directive, Drinking Water Directive etc.) • N limiting targets (N budgets) may lead to legal challenges • Time taken to create and process legislation for a N target can be longwinded and uncertain
Environmental	• Measures related to N mitigation can also mitigate other pollutants • A NUE target may have other indirect positive benefits to the environment e.g., improvements to air and water quality	• Unintended consequences of mitigation measures, e.g. decreased productivity of agriculture, displacing some production and impacts to another place • Pollution swapping (e.g. decreased NH_3 emission leading to more retained N in soil with increased N_2O emission)

9.8. Appendix H: Worked example

To aid in understanding the approach taken to calculate the impact of each measure on the NUE worked example, for slurry acidification has been presented below.

Slurry acidification can reduce the NH_3 volatilisation at the storage stage by 75% for dairy, beef and pigs. It will also reduce N_2O at the spreading stage by 23%. This measure cannot be applied on all managed livestock manure, and can be applied only where slurry is stored in tanks. Approximately, 41%, 4%, and 38% of dairy, beef, and pig excreta is on a slurry system, respectively, and approximately 50% is in slurry tanks rather than lagoons, for each livestock type. Therefore, this measure can be applied to approximately, 21%, 2%, and 19% of all dairy, beef, and pig excreta.

The relevant flows with the SNBS for these two impact values are N2O emissions from animal husbandry (including manure management), with a value of 0.92 kt N yr^{-1}, and NH3 from housing and storage of manure, with a value of 10.5 kt N yr^{-1}.

These flow values represent the absolute quantity of N transferring from the excreta pool to the atmosphere, for all livestock and storage types. Of total livestock units in Scotland, approximately 42% are beef, 11% are dairy, and 12% are pigs.

The uptake levels of this measure in 2030 is estimated to be 7%.

The current uptake is assumed to 0%.

The applicability of this measure on dairy is:

Portion of livestock that are dairy animals * portion of dairy excreta suitable for acidification

0.11 * 0.21

= 0.0228

Therefore, the impact of slurry acidification on the dairy sector is:

Applicability * (1-Current Uptake) * Impact Value * 2030 Uptake

0.0228 * (1-0.00) * -0.75 * 0.07

= -0.12%

Apply this to the absolute value for dairy from the SNBS:

10.5 * 0.0012

= 0.0126 kt N yr^{-1}

This calculation is carried out for all three livestock types, and for the N2O value. The total N saved is 0.03 kt N yr^{-1}, which is subtracted from the quantity of mineral fertiliser applied to soils:

143.78 – 0.03

= 143.74 kt N yr^{-1}

The NUE is recalculated taking into account the new mineral fertiliser quantity:

(Inputs / Outputs) * 100

(200.08 / 54.48) * 100

= 27.23%

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