Establishing a Scottish Nitrogen Balance Sheet

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Contents

Foreword

The element nitrogen is a basic building block of life, which underpins the production of food and appears in many other important processes. Nitrogen was discovered in Scotland 250 years ago, by Daniel Rutherford, the nephew of Sir Walter Scott.

The efficient use of nitrogen is important as it helps to both maximise economic benefits, for example for those producing our food through reducing wastage of nutrients contained in fertilisers, and minimise a range of harms that can occur through losses of nitrogen. These harms include contributions to climate change through emissions of greenhouse gases, impacts on human health through emissions of air quality pollutants, and impacts on biodiversity in terrestrial, freshwater and coastal ecosystems through excess nutrient inputs from both atmospheric nitrogen deposition and leaching/run-off.

The importance of nitrogen across Scotland’s economy and environment was recognised by the Scottish Parliament during the scrutiny of the Bill that became the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019. During the progress of that Bill, Scottish Ministers committed to developing the first ever statutory Nitrogen Balance Sheet for Scotland.

This commitment has been taken forward in a way that has provided key sectors and interests with an opportunity to input their views and I am grateful to all who responded to the public consultation. This input assisted with the development of this first version of the Scottish Nitrogen Balance Sheet. I would also like to express my thanks to the many technical bodies and experts that have contributed their expertise.

Scotland is the only country in the world to have enshrined in law a regularly updated, cross-economy and cross-environment Nitrogen Balance Sheet. This is a further example of our pioneering approaches in responding to the global climate emergency, as the new Balance Sheet will help to support progress to Scotland’s ambitious national greenhouse gas emissions reduction targets. As already noted, the wide scope of a Nitrogen Balance Sheet will also help support efforts to minimise other harmful effects, including on air quality and biodiversity, and the delivery of a range of benefits, particularly in relation to the efficiency of food production.

Put simply, the optimal use of nitrogen helps to ensure that economic, environmental and wellbeing outcomes can be achieved alongside one another. The Scottish Nitrogen Balance Sheet provides a powerful new, joined-up, evidence base to support these efforts.

This first version of a statutory Scottish Nitrogen Balance Sheet represents the start of the journey, rather than the final destination. This initial phase of work has highlighted and reinforced the benefits of taking a whole system approach to considering issues around how nitrogen is used in Scotland. Our work has also identified information gaps, potential improvements and challenges to be addressed in future, as part of the regular review and updating of the Balance Sheet. I look forward to working with Parliament and others with an interest in nitrogen as this work continues.

Màiri McAllan MSP,
Minister for Environment and Land Reform

1. Introduction

Why is nitrogen important?

Nitrogen is a basic building block of life. It is present everywhere across the economy and environment, forms a constituent of a wide range of materials and processes, and is especially important as a fertiliser in relation to growing and producing food.

This ubiquity means that the effective and efficient use of nitrogen is an important consideration, with far reaching consequences. Losses of nitrogen into the environment can have harmful effects on, for example, climate change, air quality, water quality and biodiversity. Optimal use of nitrogen inputs to the economy, as well as re-using and recycling any nitrogen in waste products, are key pathways for minimising such losses, whilst also maximising the benefits associated with vital processes such as food production.

What is a Nitrogen Balance Sheet?

A Nitrogen Balance Sheet, sometimes also called a Nitrogen Budget, is a way to understand and keep track of the flows of nitrogen across different parts of the economy and environment, as well as to and from other countries or regions. It then allows these flows to be analysed in a joined-up way. Summary calculations can be made of how efficiently nitrogen is currently being used and national metrics of Nitrogen Use Efficiency (NUE) are some of the key outputs from the new Scottish Nitrogen Balance Sheet (these are set out in Chapter 4 of this report).

However, it is important to appreciate that the full Scottish Nitrogen Balance Sheet (SNBS) is a far richer and more complex data source than can ever be expressed in any given set of simple summary metrics. The full initial SNBS dataset has been published alongside this report and can provide the basis for a wide range of further analyses and outputs, depending on users' interests.

Through the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019, Scotland committed to establishing a statutory whole-economy Nitrogen Balance Sheet, with regular formal review. The present report sets out the main findings from the initial version of the SNBS, and was published in December 2021 to accompany the laying in the Scottish Parliament of draft regulations to formally establish the Balance Sheet in law.

Scotland is, to our knowledge at the time of writing, the only country in the world to have enshrined in law a regularly updated, cross-economy and cross-environment Nitrogen Balance Sheet. Many other countries have carried out occasional research-focussed balance sheets, as evidenced in the European Nitrogen Assessment[1] which includes a UK nitrogen budget. However, these studies differ considerably in the flows and systems included and the methods applied in the calculations, which makes comparisons difficult. Further international benchmarking analysis of the new Scottish results is provided later in this report, where possible.

[1] European Nitrogen Assessment (2011)

What will the Scottish Nitrogen Balance Sheet be used for?

The main statutory purpose of the SNBS, as set out in section 8A(2) of the Climate Change (Scotland) Act 2009 (as amended by the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019) is to support progress to Scotland's national greenhouse gas emissions reduction targets. This is because one form of nitrogen - nitrous oxide (N_2O) - is an important greenhouse gas. Identifying opportunities for improving how efficiently nitrogen is used across key parts of the economy will, therefore, help with tackling climate change.

However, the fact that nitrogen - in all of its many forms - is basically everywhere in the economy and environment means that the evidence base provided by the SNBS also has the potential to support a range of wider policy applications. These include the development and monitoring of air quality policies (NO_x and ammonia (NH_3) being important air quality pollutants) and the identification of further opportunities to promote environmental efficiency in the production of food, natural fibres and more. As noted above, the new SNBS dataset may also assist stakeholders outside of the Scottish Government in generating their own analyses and outputs.

The publication of this initial version of SNBS represents an important step in developing the national evidence base around these matters, by bringing together data from a range of sources and providing baseline figures for nitrogen use efficiency at the national scale. Information on the future updating and further development of the SNBS, and how this relates to the wider policy context, can be found in Chapter 5.

How has the development of the Nitrogen Balance Sheet been informed by stakeholder views?

The Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 was commenced in March 2020, shortly before the extent of the impacts of the COVID-19 pandemic became clear.

An initial phase of engagement on the SNBS with key stakeholder organisations was then able to be held in Autumn 2020, as a series of online workshops. This was followed by a full public consultation from 1 December 2020 to 14 January 2021 on a set of Scottish Government proposals for key aspects of the SNBS, both in terms of its technical parameters and how its outputs might best be communicated and used to inform policy. The consultation analysis report and an initial response were published via the Scottish Government's consultation hub in March 2021[2]. The findings set out in present report represents the further development of these consultation proposals.

[2] Scottish Government consultation on the SNBS: analysis report (2021)

2. Summary of technical approach

The technical approach to the initial version of the SNBS builds from work set out in a previous technical study undertaken by the UK Centre for Ecology & Hydrology for SEPA in 2019[3]. That study made a limited, first attempt at a national Nitrogen Balance Sheet for Scotland, but with several substantial data gaps. The present SNBS builds from this, in particular by seeking to fill data gaps, broaden scope and adapt the methods to be compatible with international guidelines. Further information on the technical design of the SNBS, including the international guidelines followed, is provided in **Annex A**. However, key features are summarised below.

Nitrogen Use Efficiency (NUE) is an important summary indicator metric that can be calculated from the comprehensive dataset on nitrogen flows assembled in the SNBS. In line with the statutory requirements for the SNBS, NUE is the ratio (expressed as a percentage) of useful nitrogen-containing outputs to all nitrogen inputs. This can be expressed as shown below:

$$NUE = \frac{N\ outputs}{N\ inputs} \times 100\%$$

Calculations of NUE can be undertaken at a range of scopes and scales. Whilst sector-specific calculations (especially for crop production) are commonly used in existing international analyses, the statutory requirement for the SNBS is for a whole-economy metric, which remains a relatively novel concept. The whole-economy NUE calculations undertaken for the SNBS and summarised in Chapter 4 of this report have been undertaken in line with a 2013 OECD paper[4] and other relevant international guidance on methodology (e.g. as available from the UN Economic Commission for Europe and the EU Nitrogen Expert Panel)[5].

This first version of the SNBS draws on the latest published Official Statistics and other data sources that were available as of November 2021. This means that the majority of the data relates to nitrogen flows for the calendar year 2019, but some of the data relates to other years in the broader period 2010-2020. This is because many of the data used in the SNBS are from derived datasets dependent on the collation and processing of complex data and modelling (such as national atmospheric emission inventories), with the resulting time delay in reporting. Therefore, the baseline figures for NUE presented in this report should be understood as reflecting the most up-to-date available overall estimate for the national position as of November 2021, rather than any single specific year.

It should also be noted that the inherent uncertainties in the underlying data means that the SNBS may need to be revised in the future for purely technical reasons, as scientific knowledge improves over time or newer data become available. Such revisions have the potential to affect all historic time periods referenced, thereby potentially affecting the baseline analysis set out in this first version of the SNBS.

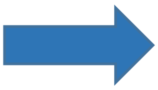
[3] A nitrogen budget for Scotland (2019) UKCEH report to SEPA
[4] OECD (2013) paper: Economy-wide nitrogen balances and indicators – concepts and methodology.
[5] EU Nitrogen Expert Panel web pages

3. Results from the initial version of the Scottish Nitrogen Balance Sheet

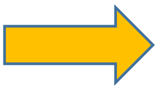
3.1 Overview

Scotland's main national nitrogen flows can be summarised in the simplified flow diagram set out below as Figure 1. The full SNBS dataset[6] contains hundreds of individual flows of nitrogen, which have necessarily been aggregated to provide such an overview.

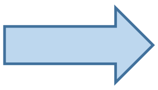
The colour coding of the flow arrows on Figure 1 reflects:



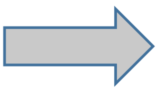
Useful (i.e. desired) nitrogen-containing outputs are shown as dark blue arrows. These include foodstuffs (cereals, fruit, vegetables, meat, dairy, eggs, fish/seafood), as well as natural fibres such as wool and wood.



Losses of nitrogen into the environment are shown as orange arrows. These include both emissions to the atmosphere (as the greenhouse gas nitrous oxide, N_2O, or as the air quality pollutants ammonia (NH_3) and nitrogen dioxide, NO_2) and flows into freshwater and coastal hydrological systems (as nitrate, NO_3, dissolved organic and inorganic nitrogen, particulates, etc).



Inputs of nitrogen are shown as light blue arrows. These mainly represent deliberate anthropogenic uses of nitrogen (e.g. fertiliser use towards food production), although there are also some inputs from natural processes (e.g. biological fixation of nitrogen from the atmosphere by terrestrial ecosystems). Also included, for the purpose of this diagram, are nitrogen flows that are recycled within the wider system before forming either a useful output or a loss to the environment (e.g. as organic materials from waste, or emissions of air pollutants that are then deposited back to soils from the atmosphere).



Grey arrows on the diagram represent instances where available data quality remains insufficient to quantify the flows. These instances mainly relate to import/export flows of nitrogen across Scotland's borders (see Annex A for more detail). Addressing these data gaps, where possible and useful to do so, will be a priority for the ongoing further development of the SNBS.

These arrows represent flows of nitrogen in a wide range of different chemical forms (e.g. nitrous oxide, ammonia, nitrates, etc.). For the purpose of the SNBS, all flows have been converted to units of kilotonnes of nitrogen per annum (kt N / yr) as a common currency which can then be added up and compared (see Annex A for technical detail of these conversion methods). The width of the arrows on Figure 1 reflect, in a general sense, the relative size of the flows.

[6] Published on the Scottish Government website alongside this report.

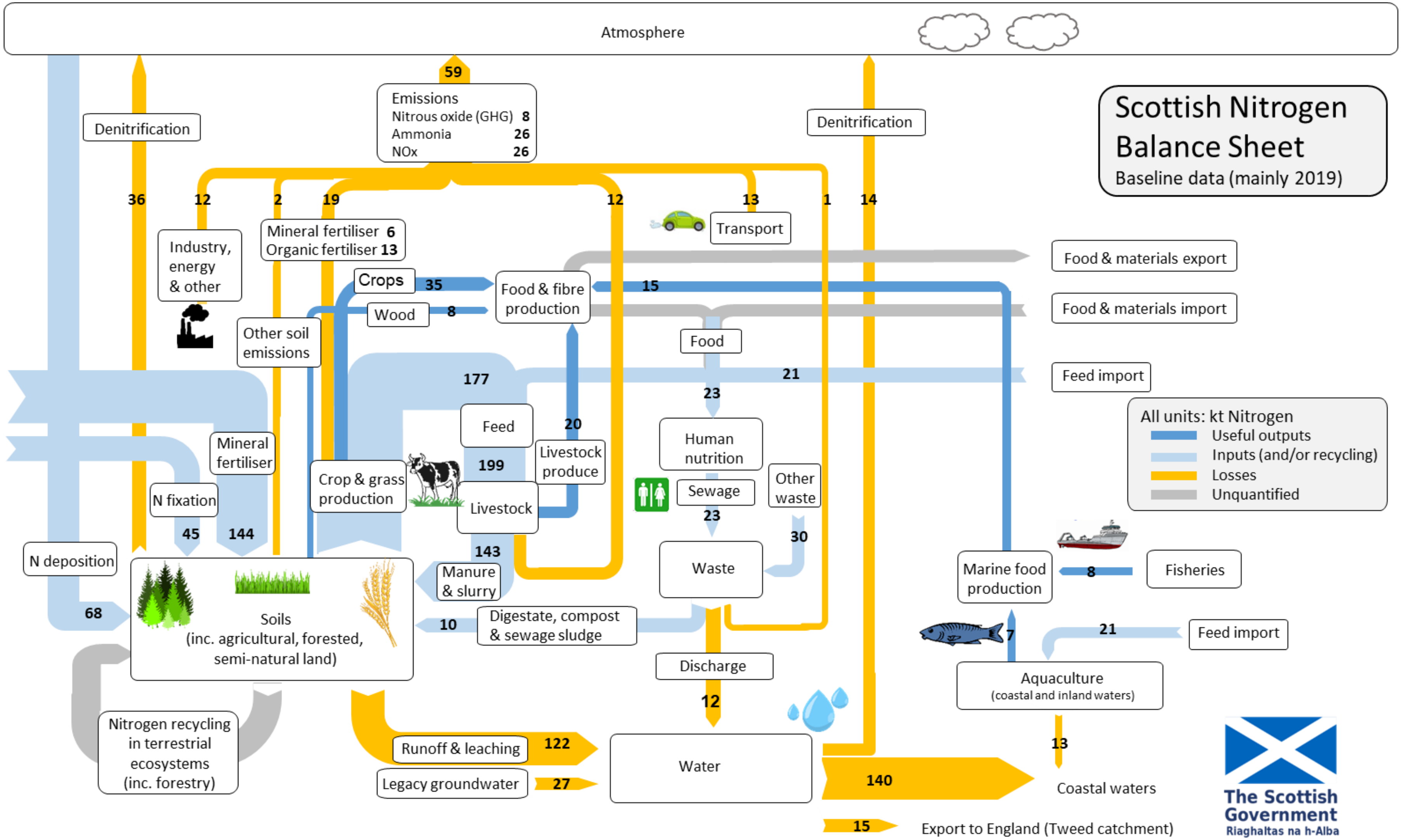


Figure 1: Nitrogen flows for Scotland (kt N / yr), combining data across all sectors of the economy and environment from latest available data (majority of data are from 2019, but with some from 2010-2020). N.B. Values may not add up due to rounding. Some minor flows (< 1kt N / yr) are not shown.

It is clear from Figure 1 that nitrogen flows across the Scottish economy and environment are highly complex, even in such a relatively simplified form. In particular, much of the nitrogen which enters into the system (e.g. from fertiliser use) is recycled within it – often in complex ways – before forming either a useful output (e.g. via food products) or a loss to the environment (e.g. via emissions to air).

Nonetheless, this summary also makes clear that by far the largest overall “engine” of nitrogen use in Scotland is associated with food production. Overall, out of the 78 kt N / yr of total useful nitrogen-containing outputs produced in Scotland, almost 90% of these are associated with food production (namely 55 kt N / yr of foodstuffs from agriculture[7], with the remainder from aquaculture and landings from sea fisheries).

The nitrogen cycle for food production is also then closely linked with the waste management aspects of the wider summary diagram, through the consumption of food for human nutrition and subsequent excretion.

There are also several sets of nitrogen flows on the summary diagram that are largely independent of the food production system, including those associated with the combustion of fossil fuels (via transport, industry and wider energy use), although these are generally much smaller in magnitude and much simpler in structure (i.e. direct emissions to the air).

Finally, it should be noted that the forestry nitrogen cycle is not set out explicitly within the format of this summary diagram, with only the useful outputs (i.e. wood products) being shown explicitly and the inputs and losses included within the wider flow arrows associated with nitrogen recycling in soils and terrestrial ecosystems (the reasons for this approach are discussed in more detail below).

The remaining sub-sections of this chapter provide further detail on the nitrogen flows for the following key sectors of Scotland’s economy and environment:

- Summary of nitrogen flows to/from the atmosphere
- Summary of nitrogen flows to/from the hydrosphere and aquatic ecosystems
- Food production: agriculture
- Food production: aquaculture
- Transport
- Industry and energy
- Humans and settlements (including waste management)
- Forests, woodlands and terrestrial semi-natural ecosystems

All of these results are at the national scale. **Annex B** sets out additional regional-scale results for some of the key hydrological nitrogen flows, where the SNBS dataset allows for such analysis.

[7] This figure includes wool production (0.8 kt N / yr).

3.2 Summary of nitrogen flows to/from the atmosphere

The atmosphere acts as both a sink for nitrogen-containing emissions from both anthropogenic activities and natural processes, and as a source of the nitrogen deposited to soils and habitats. In addition, the atmosphere acts as a transport medium, bringing imports of air pollutants to Scotland and carrying away some of the pollutants beyond Scotland's borders (this is referred to as transboundary air pollution). These flows are summarised in Figure 2 below.

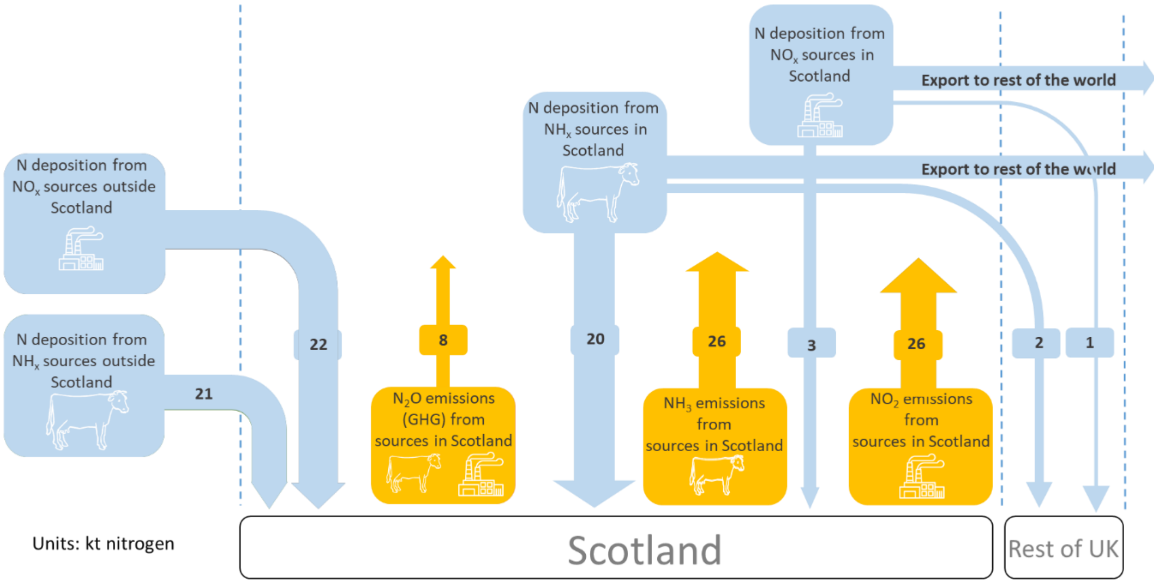


Figure 2. Atmospheric nitrogen emission and deposition flows for Scotland, covering both greenhouse gases and air quality pollutants. Emission data from the 2019 National Atmospheric Emission Inventory and GHG Inventory, deposition data from work carried out by UKCEH in support of the SNBS (Carnell et al. 2021[8]). The colour scheme is the same as for Figure 1: blue arrows represent inputs (and/or recycling) of nitrogen, yellow arrows represent losses of nitrogen.

Total emissions of nitrogen to air in Scotland amount to around 59 kt N / yr.

Nitrous oxide (N_2O), which is a greenhouse gas, amounts to around 8 kt N / yr of these total emissions. The majority of nitrous oxide emissions come from agriculture (4.8 kt N / yr) with other contributions from land use and land use change (2.5 kt N / yr) and more minor ones from industry, transport and waste processing. Nitrous oxide is a potent greenhouse gas, with a global warming potential (i.e. conversion factor to carbon dioxide equivalent) of almost 300. Scottish greenhouse gas emissions statistics for 2019 show that the 8 kt of N in the nitrous oxide emissions amounted to 3.8 Mt of CO_2 equivalent (see Annex A for further information on the conversion between these figures), which represents 8% of Scotland's total greenhouse gas emissions for that year. This makes it the third most significant greenhouse gas, after CO_2 itself (which represents 70% of the total) and methane (which represents 19% of the total).

The remaining emissions of nitrogen to the atmosphere are as other (i.e. non-greenhouse gas) air quality pollutants. These total 52 kt N / yr, split broadly evenly

[8] Carnell et al. (2021) Atmospheric modelling data for Scottish Nitrogen Balance Sheet. UKCEH Report for the Scottish Government.

between nitrogen dioxide (NO_2, 26 kt N / yr), mainly from combustion in transport, industry and wider energy use) and ammonia (NH_3, 26 kt N / yr), mainly from agricultural sources. Compared with these total air quality pollutant emissions from Scotland's territory, it is also estimated that 68 kt N / yr of nitrogen is deposited from the atmosphere, making Scotland a net importer of air pollution. The imported atmospheric nitrogen arrives in Scotland through regional and long-range transport and dispersion of air quality pollutant emissions, from both the rest of the British Isles (UK and Republic of Ireland), international shipping and the European mainland[9]. The nitrogen deposition figures in the SNBS are estimated through modelling (in combination with measurements from the UK's national monitoring networks), and data are derived annually for Official Statistics on behalf of Defra[10].

Additional nitrogen inputs to semi-natural habitats from atmospheric deposition can cause substantial biodiversity effects, damaging sensitive vegetation and the wildlife depending on it for feeding and/or breeding. Atmospheric nitrogen pollutants can also cause damage to both vegetation and human health in areas of high concentrations near the emission sources.

The spatial distribution of air pollutant emissions and atmospheric concentrations therefore matters in terms of where impacts occur. For nitrogen deposition, there are two main pathways, dry deposition (which occurs closer to the sources) and wet deposition (which can travel long distances, often many 100s of kilometres). Impacts on remote areas are typically therefore due to wet deposition, especially in high rainfall areas. By contrast, greenhouse emissions are not re-deposited, but remain in the atmosphere, contributing to climate warming on a global scale.

A further pathway of nitrogen to the atmosphere (which is not shown on Figure 1 and Figure 2) is through denitrification as di-nitrogen (N_2), which is neither a greenhouse gas nor an air pollutant. Denitrification is a microbial process that converts nitrogen from soils (especially wetlands) and water bodies through a series of reactions. Denitrification also plays an important role in sewage treatment, helping to remove nitrogen from water and thereby cleaning it. Denitrification is difficult to estimate as it involves a complex series of processes with high degrees of uncertainty. However, rough estimates can be made using existing scientific literature and expert knowledge. Overall, about 50 kt N / yr are estimated to be emitted as N_2 in Scotland, with 36 kt N / yr from terrestrial soils (including wetlands) and the remainder from hydrological systems.

3.3 Summary of nitrogen flows to/from the hydrosphere and aquatic ecosystems

Scotland's hydrosphere and aquatic (freshwater and coastal) ecosystems act as both recipients and transport media for nitrogen losses, mainly originating from anthropogenic activities but also in some cases from natural nitrogen cycling processes. The main direction of these flows is through river catchments and groundwater bodies into coastal waters.

[9] Carnell et al. (2021) Atmospheric modelling data for Scottish Nitrogen Balance Sheet. UKCEH Report for the Scottish Government

[10] National Focal Centre Trends report (2021) Trends in critical load and critical level exceedances in the UK.

The main hydrological flows of nitrogen within Scotland are due to run-off and leaching from soils, with the majority of these losses linked to grasslands (estimated at 58 kt N / yr), arable (46 kt N / yr) and semi-natural habitats (18 kt N / yr from a combination of woodlands, heaths, grasslands, montane, etc.). Discharges from sewage processing and industrial sources contribute a further 12 kt N / yr.

These sources, combined with legacy nitrates in groundwater (mainly in some aquifers in eastern Scotland and estimated at 27 kt N / yr), together contribute to a total estimated discharge of nitrogen into Scottish coastal waters of around 140 kt N / yr. A further 15 kt N / yr is exported to England via the River Tweed, which crosses the border shortly before reaching the coast at Berwick-upon Tweed.

Within coastal waters themselves, excreta from aquaculture are a further source of nitrogen input, estimated at around 13 kt N / yr.

All of the hydrological flow data described here are derived from new modelling carried out for the SNBS by UKCEH (this uses a base year of 2010)[11], apart from the information on industrial discharges and aquaculture which originate from SEPA's Scottish Pollutant Release Inventory[12] and Scotland's Aquaculture website[13].

Flows of nitrogen into the hydrosphere can lead to eutrophication, with subsequent harmful impacts of marine ecosystems. Eutrophication occurs when the enrichment of waters by nutrients (nitrogen and phosphorus) causes excessive growth of phytoplankton resulting in an undesirable disturbance of the marine ecosystem. Eutrophication is a problem if there is evidence of nutrient enrichment from human activities resulting in concentrations in seawater exceeding background concentrations. Nitrogen entering the sea from rivers, and from direct sources, undergoes complex chemical and biological processes which can lead to enrichment in some cases. This enrichment can cause direct effects such as elevated chlorophyll concentrations and increased blooms and indirect effects such as oxygen deficiency and biomass changes.

Monitoring to assess eutrophication status in the marine environment is required to develop measures and actions needed to meet our vision for clean and safe Scottish seas. In addition, such monitoring is required in order to ensure Scotland fulfils national and international obligations under environmental legislation. The most current assessment of coastal eutrophication was published as part of the Scotland's Marine Assessment 2020[14].

For Scottish Marine Regions receiving the highest nutrient inputs (Clyde, Forth & Tay, North East and Moray), there were no significant increasing trends observed (2007-2017) and inputs were lower than in the period 1990-2007. The North Coast, Orkney Islands and Outer Hebrides did show statistically significant increasing trends although loads there were typically an order of magnitude lower than the high load sea areas.

[11] Bell et al. (2021) Regional freshwater nitrogen budgets for Scotland. UKCEH Report for the Scottish Government
[12] Scottish Pollution Release Inventory SEPA online database
[13] Scotland's Aquaculture website
[14] Scotland's Marine Assessment 2020

3.4 Food production: agriculture

Agricultural activities in Scotland produce a diverse range of useful nitrogen-bearing outputs: crops (for human consumption, livestock feed, biomass and seed production) and also livestock produce (e.g. dairy, meat, eggs, wool), adding up to an estimated total of 55 kt N / yr.

The production of these outputs requires the input of nitrogen as a nutrient to soils, which happens principally through anthropogenic intervention via both mineral (artificial) fertilisers and organic manures and slurries. A total of 153 kt N / yr is estimated to be applied in this manner, which includes 10 kt of other recycled organic materials (composts, digestates, sewage sludge).

In addition to the anthropogenic inputs, 45 kt N / yr is gained from biological nitrogen fixation through legumes. This is mainly achieved through grass-clover systems, as there are only relatively small areas of peas and beans grown in Scotland. A further 12 kt N / yr is supplied by atmospheric deposition to arable and grasslands.

Finally, an estimated 21 kt N / yr of nitrogen is imported into Scotland as livestock feed (e.g. soy, maize, beet pulp, etc.) which, when combined with Scottish-grown crops and grass forage, provides a total of 199 kt N / yr of nitrogen fed to animals.

Nitrogen losses from agriculture to the environment follow two main pathways:

- emissions to the atmosphere, as the air quality pollutants ammonia (NH_3, emissions of 24 kt N / yr) and nitrogen dioxide (NO_2, emissions of 1.4 kt N / yr) and as the greenhouse gas nitrous oxide (N_2O, emissions of 4.8 kt N / yr).
- run-off and leaching from agricultural soils[15] to catchments and groundwater (flows of 104 kt N / yr, mainly as nitrates, but also dissolved organic and inorganic and particulate forms).

The data underpinning the figures set out above are based on a combination of the UK's National Atmospheric Emission Inventory (NAEI) and GHG Inventory and the underlying datasets[16] (which is based on a wide range of Official Scottish statistics for 2019), hydrological modelling commissioned by SG from UKCEH[17] (2010 data), other Official Statistics (including SEPA's Materials to Land report[18]) and expert advice from researchers at e.g. SRUC and UKCEH.

3.5 Food production: aquaculture

The dominant activity in terms of nitrogen flows for Scottish aquaculture is fin fish farming, mainly salmon in cages in coastal waters. The sector also includes the much smaller (in nitrogen terms) shellfish and freshwater aquaculture operations.

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[15] There is further run-off and leaching from other land uses, such as forestry and terrestrial ecosystems, estimated at 18 kt N / yr. This adds up to a total of 122 kt N / yr from run-off and leaching from all land uses, as summarised in Figure 1.

[16] UK National Atmospheric Emission Inventory and GHG Inventory: Online database

[17] Bell et al. (2021) Regional freshwater nitrogen budgets for Scotland. UKCEH Report for the Scottish Government

[18] Materials to land assessment (2020) report to SEPA

Useful outputs of nitrogen in harvested fish and shellfish produce are estimated at 7.3 kt N / yr, whereas the estimated anthropogenic input of feed into the system is at 21.3 kt N / yr. Losses of nitrogen into coastal waters are estimated at 13.4 kt N / yr, this being mostly in the form of nitrogen excreted by the fish, with only a small amount (estimated at 3%) of feed itself being lost.

The methodology for estimating these nitrogen flows matches that currently (Autumn 2021) used by SEPA for regulatory purposes[19], and is thought to provide a conservative set of estimates. This method is under review, and the SNBS estimates can be revisited once this has been completed.

3.6 Transport

The key nitrogen flows for the transport sector are emissions to the atmosphere (13 kt N / yr), resulting from fuel combustion. The majority of these emissions are of air quality pollutants, mainly nitrogen dioxide (NO_2, emissions of 12.4 kt N / yr), and small amounts of ammonia (NH_3, emissions of 0.3 kt N /yr). Greenhouse gas emissions of nitrous oxide (N_2O) only amount to 0.3 kt N / yr, with the main climate effect from transport sources being due to emissions of CO_2.

These figures are all taken directly from the UK's air pollutant and GHG emission inventories.

3.7 Industry and Energy

As with transport, the key nitrogen flows in the industry and energy sectors relate to fossil fuel combustion emissions to the atmosphere, totalling 12 kt N / yr. The vast majority of this is emitted as the air quality pollutant nitrogen dioxide (NO_2) with a minor contribution from ammonia (NH_3). Emissions of the greenhouse gas nitrous oxide (N_2O) only make up a small part of the overall emissions from these sectors (at 0.3 kt N / yr). This is because, again in the same way as for transport, the majority of the climate impact from fossil fuel combustion in these sectors occurs as CO_2.

The atmospheric emissions data set out above are taken directly from the UK's air pollutant and GHG emission inventories. Additional data have also been compiled from the Scottish Energy Statistics Hub[20] on the nitrogen flows associated with fossil fuels extracted on Scottish territory, and the related imports, exports.

3.8 Humans and settlements (including waste management)

Important flows of nitrogen related to human activity in Scotland include the food (i.e. protein) intake of the population and the related nitrogen excretion that is collected and processed/recycled or disposed of as sewage (around 23 kt N / yr). There are also minor emissions to the atmosphere of ammonia (NH_3, emissions of around 1 kt N / yr in total) arising directly from activities such as household solvent use, cigarette smoking, pets, babies' nappies, fertiliser application to golf courses, etc.

[19] Scotland's Aquaculture website
[20] Scottish Energy Statistics Hub website

There are then also a range of other nitrogen flows closely linked to the waste management system, comprising activities such as anaerobic digestion, composting and waste water/sewage processing. These processes allow for valuable nutrients, including nitrogen, to be recycled and utilised for growing crops and grass, and land reclamation. However, these activities as well as others within the waste sector (such as incineration and landfill) do also produce some emissions to the air.

Of a total nitrogen flow of around 30 kt N / yr from household and business/industrial waste, plus the 23 kt N / yr of human excreta generated in Scotland (see above), it is estimated that around 10 kt N / yr are applied back to Scottish soils. A further 12 kt N / yr are lost to water, of which around half is from human sewage and half from discharge by industry and food production. Atmospheric emissions from waste processing are relatively minor and estimated at less than 1 kt N / yr (mainly of ammonia and nitrous oxide). A further c. 1 kt N / yr of emission to the air, again mainly as ammonia, are associated with losses during the application of digestates and sewage sludge as fertilisers to land[21].

Other nitrogen associated with the waste sector is re-used within the Scottish economy (estimated at 13 kt N / yr) or buried in landfill sites (estimated at 9 kt N / yr). These flows are not shown as arrows on Figure 1 either for simplicity (in the case of re-use within the economy) or because they represent long-term storage of nitrogen (in the case of landfill).

All atmospheric emissions data for this sector of the SNBS are taken directly from the UK's emission inventories. Further data are taken from SEPA's Scottish Pollutant Release Inventory (SPRI) and UKCEH sources.

3.9 Forests, woodlands and terrestrial semi-natural ecosystems

Scotland's forest and woodland resource consists of different woodland types and tree species, ranging from traditional mixed Highland estates to the highly productive forests, such as the Tay Forest Park, and from urban forests in and around our cities to the more sensitive (in terms of nitrogen deposition) native woodlands, such as the Atlantic oakwoods in Argyll. These diverse and versatile forests and woodlands provide considerable economic and environmental benefits, as well as helping to improve people's quality of life.

One of the key economic benefits provided by Scotland's forests and woodlands is the production of timber and other wood fibre. It should be noted that such wood products are largely composed of carbon and contain relatively little nitrogen, compared with forest residues, including leaf litter and brash, which are generally retained in the forest where nutrients are naturally recycled. This explains why the wider forestry nitrogen cycle is not identified as a full separate set of flow arrows on Figure 1, but is instead mainly treated as part of a wider arrow related to the recycling of nitrogen within (all) terrestrial ecosystems.

[21] Within the national emission inventory structure these losses are recorded as being from the agriculture sector and are hence included (for the purpose of Figure 1) in the 19 kt N / yr of atmospheric emissions from crop and grass production.

Nonetheless, the full SNBS dataset does allow for estimates to be made of aspects of the forestry nitrogen cycle in isolation. In terms of economic production, the nitrogen in wood harvested in Scotland during 2019 was mostly destined for material (5 kt N / yr) and energetic (2 kt N / yr) uses, with a further 0.5 kt N / yr exported as roundwood (against a much smaller import of 0.1 kt N / yr).

For re-planting existing woodlands and for establishing new woodlands, nitrogen-containing fertiliser is only applied on a site specific basis where a nutrient deficiency has been identified or is highly likely, with an estimated use of only 0.02 kt N / yr. As such, the vast majority of nitrogen input to Scottish forests and woodlands occurs through either biological nitrogen fixation (11 kt N / yr) or nitrogen deposition from the atmosphere (17 kt N / yr).

High levels of nitrogen deposition can also pose challenges for sensitive near-natural woodlands, adversely affecting biodiversity - especially lichens that grow on trees and require clean air to thrive. Elevated ammonia concentrations from nearby emission sources can also have a similar effect. Official Statistics are released annually for the UK, with separate country data for Scotland, on the area of habitats and designated sites that exceed critical thresholds for atmospheric nitrogen input for ammonia concentrations (critical level exceedance) and total nitrogen deposition (critical loads exceedance)[22].

Other semi-natural habitats in Scotland, such as bogs, heathlands and montane vegetation, are similarly threatened by nitrogen input from atmospheric deposition (the SNBS estimates the deposition flow to these habitats as 33 kt N / yr).

A proportion of the nitrogen deposited from the atmosphere onto forests, woodlands and other semi-natural habitats then makes its way into waterbodies, through leaching and run-off (the SNBS estimates these flows as 18 kt N / yr)[23].

4. Baseline metrics for Nitrogen Use Efficiency

4.1 Overview

The Climate Change (Scotland) Act 2009, as amended by the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019, requires the SNBS to provide the basis of a whole-economy calculation of Nitrogen Use Efficiency (NUE).

Chapter 2 set out key elements of the methods used for this calculation and Annex A provides further technical detail. The present chapter sets out the results arising from these methods being applied to the initial version of the SNBS dataset. Whilst this chapter can be read in isolation, we would encourage readers to first familiarise themselves with the main flows of nitrogen themselves, as set out in Chapter 3.

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[22] National Focal Centre Trends report (2021) Trends in critical load and critical level exceedances in the UK.

[23] Bell et al. (2021) Regional freshwater nitrogen budgets for Scotland. UKCEH Report for the Scottish Government

In order to contextualise this analysis, which is pioneering and has only very limited international precedents at the economy-wide scale, the approach taken is to build up an understanding of NUE across key elements of the Scottish nitrogen system, starting from those where there is the greatest scope for international comparability.

4.2 Crop production Nitrogen Use Efficiency

This is the natural starting point from which to build up a wider NUE calculation, as i) crop production underpins much of wider food production, which in turn is the main engine of overall national nitrogen use in Scotland (see Chapter 3), and ii) international calculations of NUE at this level are widely undertaken.

Crop production NUE for Scotland based on the SNBS data is estimated at 65%. This reflects 58 kt / yr of useful outputs produced, relative to 90 kt / yr of inputs (a full breakdown is provided in Table 1 below).

Table 1. Crop production NUE for Scotland (all data 2019, except for N deposition which is 2018)

Inputs to arable land	kt N
mineral fertiliser	62.1
slurry/manure	17.8
atmospheric N deposition	4.0
seeds (sowing/planting)	1.7
digestate (non-crop/crop waste feedstocks only)	1.7
Biological N fixation (BNF) by arable crops	1.6
sewage sludge	1.2
Compost	0.9
total N inputs	**90.2**

Useful outputs	kt N
Food crops (inc. human-edible crops that end up as livestock feed, seed materials or biomass)	56.3
Fodder crops harvested (turnips, kale etc.)	1.9
total N outputs	**58.2**
Recycling terms (not included in either inputs or outputs for the purpose of this NUE calculation):	
digestate from crops, crop residues	

NUE = 65%

The 65% figure compares well with international data published for 124 countries (up to 2009)[24], where crop production NUE ranged from 40-77% for EU countries.

It is also important to note that NUE in arable production inherently varies depending on farm type/systems, management, environmental conditions (soils, climate), etc. While good management can reduce losses, in practice some losses *are inevitable* due to continuous nitrogen transformation processes in soils and leaching. As such, crop production NUE values between 50-90% can generally be considered desirable but there is no simple one size fits all “good value”.

[24] Lassaletta et al. (2014) 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environmental Research Letters **9:**105011.

4.3 Whole-agriculture Nitrogen Use Efficiency

For mixed crop / livestock production systems, the output side of the NUE equation expands to include animal produce, such as milk, meat, eggs or wool. On the other hand, there are now further input terms associated with the additional use of fertiliser to produce animal feed (where not already accounted for under the crop production outputs, mainly grass forage) and directly imported animal feed. Finally, it should be noted that some of the terms which were inputs to an arable-only system NUE calculation become recycling terms at this scale. For example, nitrogen in livestock manures and slurries were an external input for a crop system, whereas in a whole-agriculture system they become a recycling term.

Whole-agriculture NUE for Scotland is estimated at 27%. This reflects 55 kt N / yr of useful outputs produced[25], relative to 200 kt N / yr of inputs (a full breakdown is provided in Table 2 below, as part of a wider all-food-production analysis).

The whole-agriculture NUE figure of 27% being so much lower than the figure for crop production alone (65%) reflects the fact that livestock farming has an inherently relatively low NUE. This is because only a small proportion of the ingested nitrogen in livestock farming ends up in useful nitrogen-containing produce and most is excreted. This excreted nitrogen (and phosphorus) still constitutes a very valuable resource of nutrients. When well-managed, a greater proportion of these nutrients can be recycled, thereby reducing both losses to the environment and waste of resources through the need for additional mineral fertiliser purchase.

For Scotland, a simple feed-conversion calculation would result in a rough value of c. 10% NUE for livestock activity if this were taken in isolation (i.e. nitrogen in livestock produce 20 kt N / yr of useful outputs, versus inputs of nitrogen in livestock feed of 199 kt / yr). Such a value is broadly consistent with international comparisons for livestock feed conversion efficiency.

As such, any country with an agriculture sector that contains a relatively large proportion of livestock, especially of ruminants (pigs & poultry have relatively better feed conversion ratios for nitrogen than cattle and sheep, but only ruminant livestock can utilise the very large area of Scottish land that is not suitable for growing crops), will always have a relatively low set of overall NUE values.

It should also be noted that, at any given point in time, there is a considerable amount of nitrogen present in living animals (as protein). This could be considered as “stocks”, functionally equivalent to the nitrogen bound up in living vegetation or soils (see Chapter 3). However, for the purpose of a long-term (e.g. annually averaged) calculation of NUE, such nitrogen is neither an input nor an output (nor a loss) term and therefore does not feature in the breakdown in Table 2.

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[25] When compared with Table 1 figures above for crop production (with 58 kt N / yr useful output), the apparently smaller total useful output shown here for whole-agriculture (55 kt N / yr) is related to a substantial proportion of the outputs becoming recycling terms at this scale of NUE calculation. For example, in the whole-agriculture system, crops grown specifically as livestock feed (including human-edible crops such as cereals fed to livestock) are removed from the output side of the NUE equation, in the same way as manures are removed from the input side.

4.4 Aquaculture Nitrogen Use Efficiency

A simple feed conversion NUE calculation can also be carried out for the aquaculture sector, which in Scotland is dominated by salmon farming in coastal waters. **This results in an estimated NUE value for aquaculture of c. 34%.** This reflects useful output products of 7 kt N / yr, relative to inputs of 21 kt N / yr (a breakdown is provided in Table 2 below, as part of a wider all-food-production analysis). Of these useful outputs, the vast majority are from finfish production in coastal waters, i.e. mainly salmon farming, with the remainder split between freshwater finfish (mainly trout) and shellfish.

The feed conversion NUE value is higher for aquaculture (c. 34%) than it is for agricultural livestock (c. 10%), as fish are cold-blooded and a larger proportion of their feed is converted into protein.

4.5 All-food-production Nitrogen Use Efficiency

By combining the SNBS data across the agriculture and aquaculture sectors, a value for **all-food-production NUE can be estimated as 28%**. This reflects total useful outputs of 62 kt N / yr, relative to total inputs of 221 kt N / yr (a full breakdown is provided in Table 2 below).

The all-food-production NUE figure is dominated by the much larger overall magnitude contribution from agriculture (with an estimated NUE of 27%), slightly increased by the contribution from aquaculture (with an estimated NUE of 34%).

Table 2. Food production NUE for Scotland (all data 2019, except for N deposition which is 2018)

Inputs (to the food production system)	**kt N**
mineral fertiliser	143.8
livestock feed (not grown in Scotland, e.g. soy)	21.4
Aquaculture feed	21.3
biological N fixation (BNF) by legumes	18.1
atmospheric N deposition (to arable and grass)	12.1
sewage sludge to agricultural land	2.4
digestate (non-agricultural feedstocks only)	2.0
compost to agricultural land	0.9
Seeds (sowing/planting) net import	-0.7
total N inputs	**221.4**

Useful outputs	**kt N**
harvest (as food, exc. human-edible crops used as livestock feed or seed)	34.8
livestock produce (milk, eggs, meat, wool)	19.6
harvest (finfish)	7.1
harvest (shellfish)	0.3
total N outputs	**61.8**

NUE = 28%

Recycling terms (not included in either inputs or outputs for the NUE calculation):
Manure, slurry, digestate of agricultural origin, crop residues, fodder crops grown in Scotland

4.6 Whole-economy NUE

An economy-wide NUE figure can then be arrived at by taking the all-food-production analysis and adding in the remaining SNBS sectors of forestry, transport, industry, energy and waste management.

The estimated value of the baseline[26] figure for economy-wide NUE is 25%. This reflects total useful outputs of 78 kt N / yr, relative to total inputs of 308 kt N / yr (a full breakdown is provided in Table 3 below).

In visualising such a whole-economy NUE calculation, it may also be helpful for readers to refer back to Figure 1. The useful output arrows on this diagram (those in dark blue) refer to the same terms as set out in Table 3 above for the whole-economy NUE calculation. However, it should be noted that both the inputs and recycling terms in the context of this calculation are shown as being the same colour for the purpose of Figure 1 (i.e. as the light blue arrows). This approach is due to the complexity of the system boundaries for this scale of NUE calculation which, if reflected in full on Figure 1, would result in many additional smaller arrows needing to be included and a corresponding loss of accessibility. For example, only the part of N deposition that originates from emissions outside of Scotland represents an input at the whole-economy scale, whereas emissions to the atmosphere in Scotland depositing back to Scottish soils constitute a recycling term.

Table 3. Whole-economy NUE for Scotland (as of baseline period)

Inputs (at whole-economy level)	kt N
mineral fertiliser (all land)	143.8
biological N fixation (all land)	45.0
atmospheric N deposition (imported NOx + NHx only)	44.5
NOx emissions from fuel burnt in Scotland (to account for transport & energy)	24.3
livestock feed (not grown in Scotland)	21.4
aquaculture feed (assumed to be mostly imported)	21.3
import: fishery landings	8.4[27]
import of wood	0.1
seeds (net import)	-0.7
import: consumer goods, food etc.	n/a[28]
total N inputs	**308.2**

Useful outputs	kt N
harvest (as food, excl human-edible crops used as livestock feed or seed)	34.8
livestock produce (milk, eggs, meat, wool)	19.6
import: fishery landings	8.4[27]
Forestry harvest - all uses (inc. export)	7.5
aquaculture produce (finfish, shellfish)	7.3
exported materials	n/a[28]
total N outputs	**77.7**

Recycling terms (not included in either inputs or outputs for the NUE calculation):
Manure, slurry, digestate of agricultural origin, crop residues and fodder crops produced in Scotland, atmospheric N deposition (where the NOx and NH_3 originated from Scottish emissions)

NUE = 25%

[26] The baseline data set out in Table 3 is mainly for 2019, but - as explained in Chapter 2 - this should be understood as reflecting the most up to date information available as of November 2021.
[27] For the purpose of a whole-economy NUE calculation, fisheries are recorded as *both* an input to the economy (i.e. fish landed in Scotland) and a useful output (as they will be used as foodstuffs).
[28] The data necessary to quantify the amounts of nitrogen in materials imported and exported do not currently exist in sufficient detail and quality. See Annex A for further information.

The economy-wide NUE figure for Scotland of 25% is dominated by the NUE value associated with food production (of 28%), as this forms by far the largest overall part – and core engine – of the SNBS as a whole.

Nonetheless, the addition of the other sectors does slightly reduce the economy-wide figure relative to the food-production one. There are several factors behind this, all of which carry substantial technical complexities:

- For the transport, energy and industry sectors, the useful outputs from these combustion processes are heat, energy and mobility. As these contain no nitrogen, these sectors inherently have an effective NUE value of zero. Nonetheless, these sectors do contribute NOx emissions from fuel burnt in Scotland and are statutorily required to be taken into account for the purposes of the relatively novel whole-economy NUE metric and can be done so on the basis laid out in an OECD paper[29].
- The forestry sector could be considered to have an effective NUE value of c. 27%, based on production of 8 kt N / yr as useful nitrogen-bearing outputs (for material use, wood fuel and export), from 28.2 kt / yr of inputs. However, it is noted that this is not a very useful indicator – as anthropogenic fertiliser input to tree planting is relatively very small and the vast majority of nitrogen inputs to forests and woodlands are from atmospheric deposition and biological N fixation (this is explored further in the section on forestry in Chapter 3).
- For the waste management sector, NUE is simply not a sensible indicator, as almost all of the flows represent recycling from other sectors as composts, digestates and sludges.
- Further information on technical issues associated with avoiding double counting in an economy-wide NUE calculation can be found in Annex A.

As of the time of publication of this report there are, to our knowledge, no existing international comparators for such a comprehensive and detailed economy-wide NUE calculation. However, efforts are understood to be underway over the next year, through the UN Economic Commission for Europe (ECE) Task Force on Reactive Nitrogen, to encourage and enable countries to use the UN ECE guidance for national nitrogen budgets (see Annex A) to report economy-wide NUE estimates. In this context, Scotland's SNBS plays a pioneering role on the international stage.

5. Policy context and next steps for the Scottish Nitrogen Balance Sheet

5.1 Overview

The statutory requirements for the SNBS, as set out in the Climate Change (Scotland) Act 2009, as amended by the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019, are to quantify nitrogen flows across Scotland's economy and environment to support a purpose of recording how nitrogen use efficiency contributes to the achieving of Scotland's national targets to reduce greenhouse gas emissions.

The information provided in the initial version of the SNBS dataset and summarised in this report has set out the main uses of nitrogen across the Scottish economy and

[29] OECD (2013) paper: Economy-wide nitrogen balances and indicators – concepts and methodology.

environment, including the main current sources of nitrous oxide emissions (which is a greenhouse gas). In particular, as set out in Chapter 3, the 8 kt N / yr of nitrous oxide emissions recorded in the SNBS (which are mainly from food production, with secondary contributions from other sectors) account for around 8% of Scotland's total greenhouse gas emissions (based on 2019 data).

However, as the results in Chapter 3 also make clear, nitrous oxide emissions also only form a relatively small, although certainly very important, part of the wider picture of nitrogen flows in Scotland. The Scottish Government is committed to improving air quality, water quality, nature and biodiversity outcomes, alongside tackling climate change, and recognises that the evidence from the SNBS has wide relevance across a range of policy areas.

5.2 Summary of existing policy frameworks

The Scottish Government has a range of strategies and policy initiatives in place, across sectors of the economy, which can be expected to improve the use of nitrogen and thereby reduce the harms caused by losses into the environment. These measures include;

The Scottish Government's approach to reducing greenhouse gas emissions (including nitrous oxide), across all sectors of the economy and over the period to 2032, is set out in the updated Climate Change Plan[30]. This includes a range of measures that can be expected to improve the efficiency of nitrogen use within food production, such as increasing uptake of climate mitigation measures by farmers, crofters, land managers and other primary food producers; increasing awareness and knowledge transfer and reduced emissions from nitrogen fertiliser, along with improved storage and use of slurry. The Plan also includes a range of policies to reduce dependence on fossil fuel combustion across sectors (including transport, industry and wider energy use), for example by shifting to electric vehicles, supporting active travel choices and supporting renewable energy technologies, all of which will help reduce nitrous oxide emissions from these sectors. The Plan also includes a range of policies to reduce the environmental impacts of waste management processes and support a transition towards a more circular economy, for example, delivering against our ambitious target to reduce food waste by one third by 2025 (against a 2013 baseline), through the Food Waste Reduction Action Plan, which will reduce nitrogen losses associated with food production and consumption.

Since the publication of the updated Climate Change Plan a number of further actions with relevance to improving nitrogen use have also been set out. A £51 million National Test Programme for agriculture has been announced which will support our farmers and crofters to learn how their work impacts on climate and nature and to help us understand how sustainable farming can be supported and rewarded in future. All farmers will be both encouraged and supported to take forward carbon audits and/or nutrient management plans and we will be considering how sustainable farming can be supported and rewarded in future, working with a focus group of farmers and crofters. This builds on a range of existing support,

[30] Securing a green recovery on a path to net zero: the Climate Change Plan 2018–2032 update

including grants and advice through the Farm Advisory Service which provides bespoke advice to farmers, crofters and land managers and Farming for a Better Climate which provides practical support to benefit the farm and help reduce our impact on the climate.

In addition, amendments have been made to the Water Environment (Controlled Activities) (Scotland) Regulations 2011. These include improving controls on the storage of slurry and digestate to reduce leakage, and more targeted spreading to maximise the nutrient benefit and reduce emissions.

In terms of air quality pollutants (including ammonia and NO_2), the Scottish Government in July 2021 published the Cleaner Air for Scotland 2 (CAFS 2)[31] strategy, which sets out the policy framework for further air quality improvements over the period 2021-2026 to protect human health and the environment, and to fulfil legal responsibilities. It is recognised that NO_2 emissions from transport and combustion more generally can have a significant impact on human health, with high concentrations present close to busy roads. CAFS 2 contains a wide range of actions across a number of policy areas which will contribute to reductions in nitrogen emissions. Among the many transport related actions which will play an important role is the introduction of Low Emission Zones that set minimum emission standards for vehicles entering the four cities of Glasgow, Edinburgh, Aberdeen and Dundee. The latest Euro 6 (VI) technologies to reduce NO_x emissions work predominantly through Selective Catalytic Reuptake in the exhaust system, that injects an ammonia based solution to reduce NO_x to N2.. CAFS 2 also includes several actions intended to reduce nitrogen emissions from agricultural activities, with a particular focus on ammonia.

Woodland creation and management in Scotland are underpinned by the internationally recognised principles of Sustainable Forest Management – as defined in The UK Forestry Standard (UKFS[32]). The UKFS is the technical standard for forestry in Scotland and sets out the legal and good practice requirements to be followed, and through detailed guidelines it gives considerable safeguards to protect the environment, aspects of which have relevance to the nitrogen cycle:

- With regard to water protection in acid sensitive catchments, UKFS requires that where new planting or replanting of existing woodland is proposed within the catchments of water bodies at risk of acidification, an assessment of the contribution of forestry to acidification and the recovery process should be carried out; details of the assessment procedure should be agreed with the water regulatory authority.
- The UKFS also requires that forest soil fertility levels should be maintained to safeguard the soil's character and productive potential. To achieve this, one important aspect is to ensure the removal of forest products from the site, including non-timber products, does not deplete site fertility or soil carbon over the long term and maintains the site potential.

31 Cleaner Air for Scotland 2 - Towards a Better Place for Everyone Scotland's new air quality strategy
32 The UK Forestry Standard (UKFS) The governments' approach to sustainable forestry

5.3 Next steps for the Scottish Nitrogen Balance Sheet

This initial version of the SNBS is only the start of a journey, with the full expectation that the evidence base and its applications will continue to develop and evolve. The immediate next step (following December 2021) will be the scrutiny process in the Scottish Parliament of the draft regulations to formally establish the SNBS in law, which have been laid at the same time as publication of the present report. There is a statutory deadline for this establishment process to have concluded by 23 March 2022.

Based on the proposals set out by the Scottish Government in the draft regulations, the SNBS would be subject to annual review and updating (starting from 2023). Should this approach be agreed by the Parliament, each such round of review would provide an opportunity to incorporate more recent and/or updated data (where this has become available) into the SNBS and also to continually improve the technical methods and output formats.

Regular updating of the SNBS dataset would also allow for tracking over time of the associated estimates of economy-wide NUE. This would, in turn, enable Scotland to monitor improvements and efficiency gains in nitrogen use, which will mainly manifest themselves in the reduction of the harms associated with losses to the environment (both of greenhouse gases and other pollutants).

In parallel to such a programme of ongoing technical development and monitoring of the SNBS, the Scottish Government will also continue to explore opportunities to integrate the new evidence provided by the SNBS into wider policy frameworks and structures. For example, we have committed in the monitoring framework for the updated Climate Change Plan (which is reported on each May) to exploring the development of a policy outcome indicator for the agriculture sector that draws from the new information on nitrogen use efficiency available through the SNBS. We will also consider actions that can improve nitrogen use efficiency as part of the agriculture National Test Programme. One of the actions contained in the Cleaner Air for Scotland 2 Strategy is to ensure that the new evidence base from the SNBS is used to inform future policy making around air quality.

In conclusion, the SNBS provides a new, cross-cutting overview of nitrogen flows across all sectors of the Scottish economy and environment. Its ongoing future development and monitoring will help support a range of Scottish Government policies - both existing and under development – aimed at maximising the benefits associated with nitrogen use, whilst minimising losses to the environment.

Annex A – Additional technical information

Methodology for estimating the nitrogen flows which comprise the SNBS

Over recent years, an international agreement under the Gothenburg Protocol to the UN Economic Commission for Europe (ECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP) has established an international reporting scheme for some key aspects of nitrogen flows. A guidance document on national nitrogen budgets[33] was developed by the UN ECE Task Force on Reactive Nitrogen's Expert Panel on Nitrogen Budgets[34] and contains detailed draft annexes outlining the recommended methodology[35]. This guidance builds on existing national data collections wherever possible, including the international greenhouse gas and air quality pollutant emission inventory reporting mechanisms and the OECD/EUROSTAT methodology[36] for Gross Nutrient Budgets (GNB, formerly known as Gross Nitrogen Balances). The SNBS has been developed using the UN ECE guidance documents where possible. So far, to our knowledge, only Germany has published a national nitrogen budget that is largely, but not entirely, based on this draft guidance[37].

The SNBS re-uses existing published Official Statistics, such as the GHG and air quality emission inventories and SEPA pollutant datasets, where available. Additional information has been gathered from key expert institutions such as Scotland's Rural College (SRUC), SEPA, Forest Research, the UK Centre for Ecology & Hydrology (UKCEH), and Rothamsted Research. All of these data sources are documented in detail in the SNBS spreadsheet. For some less well understood nitrogen flows, default values have been applied to relevant activity data, in the same way as for Tier 1 emission inventory methodologies (i.e. the use of simple emission factors). This approach ensures consistency and compatibility with existing long-term statistics data series wherever possible, and will aid the development of a time series where trends in nitrogen flows can be observed over time.

The UK's atmospheric emission inventory reports air quality pollutants in their full chemical composition - for example, ammonia is reported as amounts of NH_3 rather than as amounts of N alone. Furthermore, emissions of non-CO_2 greenhouse gases (including N_2O) are reported within the national greenhouse gas inventory as CO_2 equivalents through use of GWP conversion factors (see Chapter 2). To convert these published emissions data into the common unit for the SNBS (of kt N / yr), which relates to flows of nitrogen (only), a conversion is undertaken based on the respective molecular weights (where Nitrogen (N) = 14, Hydrogen (H) = 1 and Oxygen (O) = 16)[38]. For example, ammonia (NH_3) consists of one molecule of Nitrogen and 3 molecules of Hydrogen, therefore the total molecular weight of NH_3 =

[33] UN ECE (2013) Guidance document on national nitrogen budgets
[34] UN ECE Task Force on Reactive Nitrogen (TFRN): Expert Panel on Nitrogen Budgets (EPNB) webpages
[35] UN ECE (2021) Guidance document on national nitrogen budgets: draft detailed annexes.
[36] European Commission EUROSTAT (2013) Methodology and Handbook Eurostat/OECD Nutrient Budgets.
[37] Reactive nitrogen flows in Germany 2010 - 2014 (2020) report
[38] Also referred to as atomic number – see for example Periodic Table of Elements - PubChem (nih.gov): select "atomic number" as display property

14 + (3 x 1) = 17. To convert the amounts of such emissions as reported in the national inventories into flows of nitrogen alone, these values need to be divided by the total molecular weight (17) and multiplied by that of the nitrogen present (14).

Methodology for estimating Nitrogen Use Efficiency (NUE) metrics

As set out in Chapter 2 and Chapter 4 of this report, NUE calculations can be derived for some individual sectors of the economy, and also at the whole-economy level. The former is much more commonly used in existing international analysis, with widespread application in particular for crop production systems.

A key question to consider when calculating NUE for any system is the definition of the system boundaries. This determines which parameters should be used on the input and output sides of the NUE equation, and which become internal to the calculations, as “recycling terms” within the system.

Using the example of crop production systems, the useful outputs are defined as the nitrogen contained in harvested crops removed from the land. Inputs include purchased (mineral) fertilizers, livestock manures and slurries, composts or other organic materials that aren’t recycled within the system, planting materials, but also atmospheric deposition and biological nitrogen fixation by legumes.

Alternatively, if the scope of the NUE calculation is then expanded to cover a mixed crop/livestock agriculture system, the useful outputs also include animal produce, such as milk, meat, eggs or wool. However, in this case manures become a “recycling term” within the systems boundaries rather than an input (as was the case for the crop production example).

Forestry can be considered as a further example, illustrating an instance where the “recycling terms” become relatively very important for an NUE calculation. In this case, both the useful outputs (mainly wood) and inputs (mainly from atmospheric deposition and biological nitrogen fixation) hide a wide range of other processes. In other words, large amounts of nitrogen are locked up in woodland as stocks, and much internal recycling of e.g. leaf litter, or brash etc. left behind after felling operations.

The main elements of the definitions of system boundaries and recycling terms used in the calculation of whole-economy NUE that forms the main output from the SNBS are explained in Chapter 4. However, further more technical points are:

- To avoid any double counting at this scale of calculation, the Nitrogen deposition caused by local emissions (i.e. re-deposition of Scottish emissions on the Scottish territory, derived from modelling) was removed from the input side of the NUE equation.
- Similarly, ammonia deposition originating from emissions from within Scotland becomes a recycling term in the whole-economy approach, and therefore only deposition imported to Scotland from across the border is counted as inputs.
- On the other hand, Nitrogen fixation (on the input side) is estimated for the whole territory, rather than agricultural and forestry land only.
- Fish landings are included on both the input and output sides of the economy-wide NUE calculation, i.e. they are landed at Scottish ports and therefore are

an input to the Scottish economy, and also a useful output (as food). Thereby this term effectively cancels out within the calculation.

- As noted in the subsection below, the import and export of goods and materials across the Scottish border represents an uncertainty in the current calculation (as insufficient data currently exist).

As well as the choices of scale (both in terms of sectors vs whole-economy and spatial scale), NUE metrics will also be influenced by the length of the time period under consideration. This is especially important given the potential for natural variations in the nitrogen locked-up temporarily in “stock” (for example livestock on farms, or trees in the context of forestry activities). However, as the NUE outputs from the current SNBS are using a national, whole-economy scale, an annual (or indeed multi-annual) summary NUE value for Scotland should provide a valid methodology for establishing trends over time.

Summary of current data gaps for the SNBS

The main remaining data gaps in the SNBS (i.e. the grey arrows in Figure 1) can be summarised as follows:

Detailed import/export statistics for volumes of goods and materials can generally only be obtained at the UK level, and not enough detail is currently available to extract data for Scotland from the few data sources that do exist (e.g. summary HMRC statistics, Input-Output tables). Partial import/export data are available or can be reasonably inferred, but only for some specific sub-sectors of the economy (e.g. data exists on roundwood exported from Scottish forestry, or any use of soya as animal feed in Scotland can be assumed to be imported). The Scottish Material Flow Accounts[39] also attempt to derive some flows of materials and produce from the available statistics, but there remain significant data gaps.

In addition to these trade flows, there are some natural processes in terrestrial (and aquatic) ecosystems where nitrogen is taken up and recycled, such as through the senescing and decomposition of vegetation, and these are also not quantified here. These processes, which occur across all types of vegetation, woodlands, heathlands, etc. are distinct from those described for forestry operations and the other specific cases covered in Chapter 3, where data does exist. These processes are acknowledged as difficult to quantify in the UN ECE guidance and the scientific knowledge the guidance draws on, and data are not required for any of the NUE calculations set out in this report.

There is also currently very limited knowledge on the extent of clover on Scotland’s pastures, and no specific data exist to our knowledge. If this could be improved, it would assist with the quantification of the biological nitrogen fixation for agriculture in the SNBS.

In terms of scope for improving the secondary calculation methods (rather than the underpinning data or main economy-wide NUE calculation methods), there are several potential areas for future improvement:

[39] Material Flow Accounts for Scotland (2021) Report and data by Zero Waste Scotland

- Agriculture livestock feed conversion calculations: The simple calculations applied in Chapter 4 are based on work by SRUC[40] and its representation in Scotland's Material Flow Accounts (MFA)[41]. It would be preferable to develop these into more comprehensive approaches, should further relevant data (e.g. around the nitrogen content of the wide range of grassland types in Scotland and how these feed into the different livestock sectors) become available in the future.
- Aquaculture livestock feed conversion calculations: The estimates of feed conversion and losses in Chapter 4 are based on the current modelling used by SEPA for regulatory purposes. However, SEPA recently started a review of their evidence base, and any outcomes should be incorporated into the relevant SNBS calculations once the review has been completed.

[40] Leinonen et al. (2019) Applying a process-based livestock model to predict spatial variation in agricultural nutrient flows in Scotland. Journal of Cleaner Production 209:180-189.
[41] Material Flow Accounts for Scotland (2021) Report and data by Zero Waste Scotland

Annex B – Regional scale results

As part of the initial phase of the SNBS, additional technical work was commissioned by the Scottish Government on regional freshwater nitrogen budgets for Scotland[42]. This has estimated, using the freshwater model 'LTLS-FM', hydrological nitrogen flows during 2010 for 10 regions delineated under the Water Framework Directive, as Sub-Basin Districts/Area Advisory Group boundaries (as shown in Figure 3).

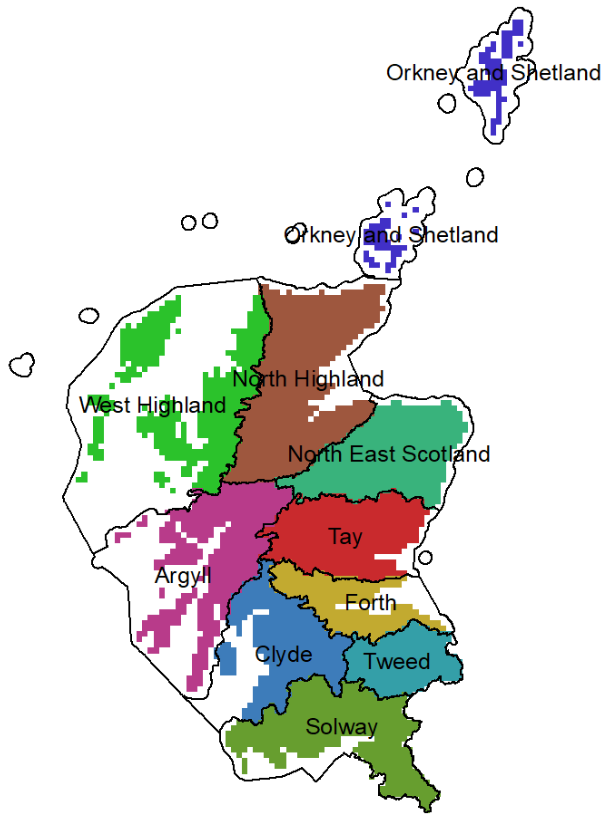

Figure 3 - Sub-Basin Districts/Area Advisory Group boundaries for 10 regions, as delineated under the Water Framework Directive and used for regional modelling of hydrological nitrogen flows with the model LTLS-FM.

These regional N budgets quantify key hydrological flows across agricultural and semi-natural systems, including nitrogen from human waste and atmospheric deposition, and show the relative importance of different flow terms across different regions. This type of analysis can help inform land use policy development as to key hydrological nitrogen loss pathways for each region, integrated across agriculture, human settlements etc.

The results are summarised in Figure 4 and indicate that total N inputs vary substantially between regions, from 1.7 kt N / yr for Orkney and Shetland to 33.2 kt N / yr for NE Scotland. However, if N inputs are divided by the area of the region, it becomes apparent that two of the smallest regions, Tweed and Forth, have the highest N inputs / km^2. The total (i.e. national) estimated losses of freshwater N to

[42] Bell et al. (2021) Regional freshwater nitrogen budgets for Scotland. UKCEH Report for the Scottish Government

coastal waters were 151 kt N / yr (with up to 68% of these flows originating in agricultural land management) and those to the atmosphere were 17.3 kt N / yr, with more than half of the N losses originating from just 3 regions (Tay, Solway and NE Scotland) [43].

[43] N.B. the data for the sub-basins include areas of England in the Solway and Tweed catchments. These have been adjusted for the SNBS outputs in the main report, where all data refer to Scotland's territorial boundaries. For example, the Tweed catchment does not flow directly from Scotland into coastal waters, but hydrological flows are exported across the border to England, from where they then flow into England's coastal waters.

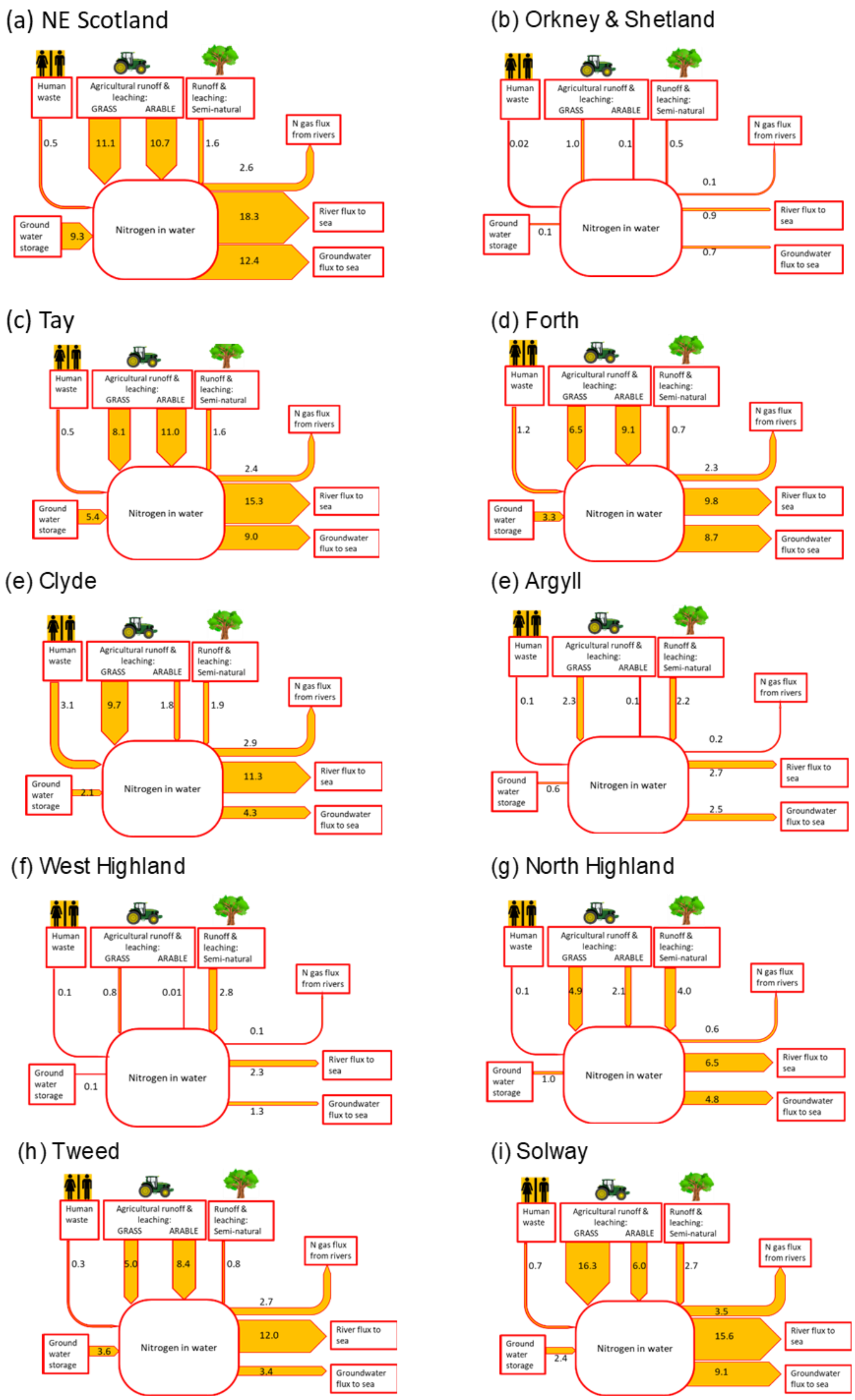

Figure 4 – Hydrosphere/soil nitrogen flows (units are kt N / yr, data is for 2010) quantified for the 10 Sub-Basin Districts/Area Advisory Group boundaries for 10 regions, as delineated under the Water Framework Directive and estimated with the LTLS-FM macronutrient model at a 5 km by 5 km grid. Arrow widths are proportional to N flows.

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