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Agriculture, Environment and Marine

Scottish Nitrogen Balance Sheet 2020

Summary

Nitrogen Use Efficiency (NUE) is a summary indicator which can be calculated from the nitrogen flows in the Scottish Nitrogen Balance Sheet (SNBS). NUE is the ratio (expressed as a percentage) of useful nitrogen-containing output to all nitrogen inputs.

Table 1: Summary measures of Nitrogen Use Efficiency

	Nitrogen input (kt N / yr)	Useful nitrogen output (kt N / yr)	Nitrogen use efficiency
Arable	93.1	58.2	62.5%
Livestock	197.3	20.0	10.1%
All Agriculture	187.7	55.4	29.5%
Aquaculture	23.1	6.9	29.9%
All Food	210.8	62.3	29.6%
Forestry	28.2	7.7	27.3%
Whole Economy	**290.6**	**78.1**	**26.9%**

Note: Sectors of the economy not included in the above table have no significant useful outputs, and so if their Nitrogen Use Efficiencies were to be calculated they would be 0%.

In 2020, the whole economy NUE figure was 26.9%. Although the whole economy figure is dominated by food production, this figure is lower than the NUE for food production due to the inclusion of sources such as transport which produce no useful nitrogen outputs. The NUE for all food production is 29.6%, with the figures for aquaculture (29.9%) and agriculture (29.5%) being very similar. The 29.5% figure for all of agriculture comprises two extremely different values for arable agriculture (62.5%) and livestock based agriculture (10.1%). Livestock based agriculture is inherently less nitrogen efficient than arable agriculture because only a small proportion of the ingested nitrogen by livestock ends up in useful nitrogen-containing produce.

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 section Nitrogen Use Efficiency 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 (Nitrogen Balance Sheet) (Scotland) Regulations 2022, Scotland has committed to establishing a statutory whole-economy Nitrogen Balance Sheet, with regular formal review.

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.

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[1] European Nitrogen Assessment (2011)

What is the Scottish Nitrogen Balance Sheet used for?

The main statutory purpose of the SNBS 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.

Flows of Nitrogen in the Scottish Economy

Overview

The full SNBS dataset contains hundreds of individual flows of nitrogen, which have been aggregated to provide overviews in the sections below[2]. It is clear that nitrogen flows across the Scottish economy and environment are highly complex. 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, by far the largest overall "engine" of nitrogen use in Scotland is associated with food production. Overall, out of the 78.1 kt N / yr of total useful nitrogen-containing outputs produced in Scotland, almost 80% of these are associated with food production (namely 55.4 kt N / yr of foodstuffs from agriculture, with the remainder from aquaculture and landings from sea fisheries).

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

There are also several sets of nitrogen flows 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).

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[2] The initial release of the SNBS in 2021 included an indicative diagram of the main nitrogen flows in Scotland. Nitrogen flow diagram

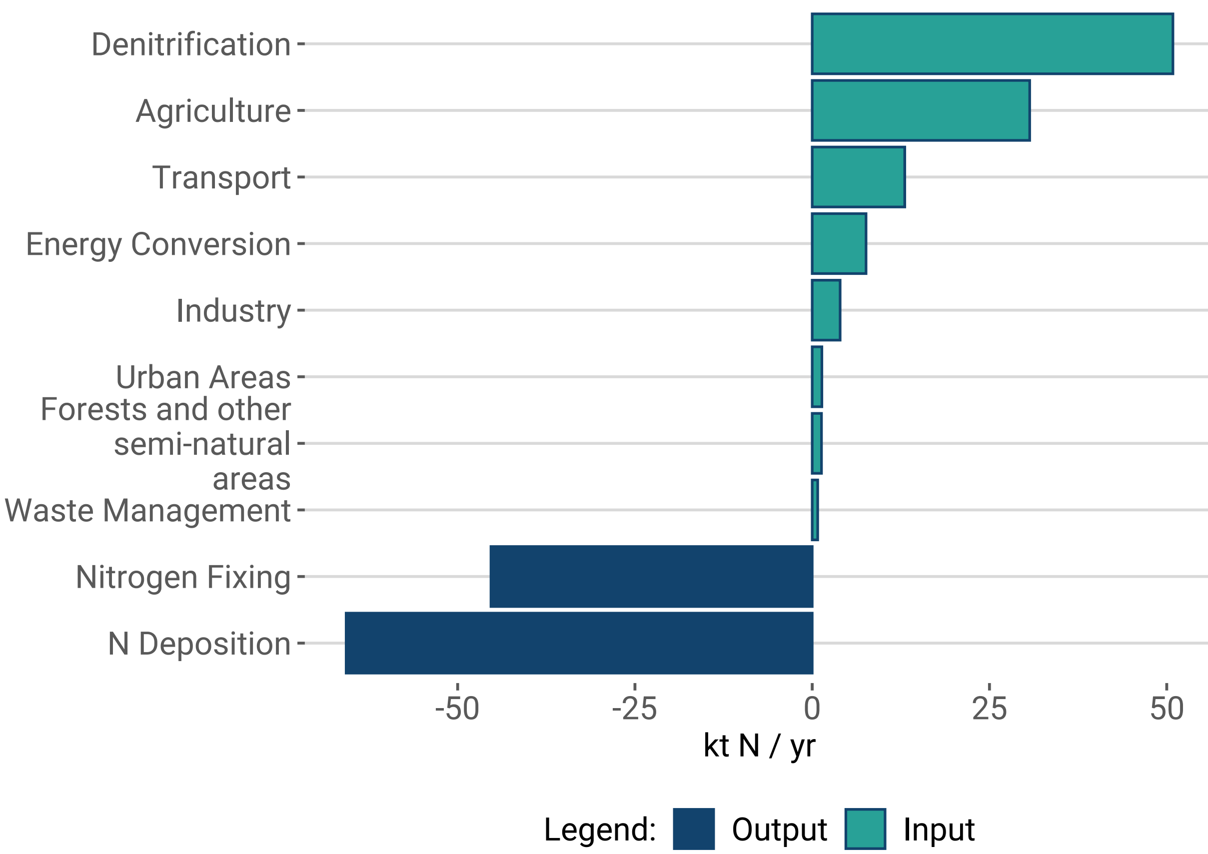
The remaining sub-sections of this chapter provide further detail on the nitrogen flows for key sectors of Scotland's economy and environment. All of these results are at the national scale.

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).

Total emissions of nitrogen to air in Scotland amount to around 58.7 kt N / yr.

Figure 1 Flows of nitrogen into and from the atmosphere. Values in kt N per year.



Nitrous oxide (N_2O), which is a greenhouse gas, amounts to around 7.8 kt N / yr of these total emissions. The majority of nitrous oxide emissions come from agriculture (5.5 kt N / yr) with other contributions from land use and land use change (1.5 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 298. Scottish greenhouse gas emissions statistics for 2020 show that the 7.8 kt of N in the nitrous oxide emissions amounted to 3.7 Mt of CO_2 equivalent, which represents 9.1% 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 65.8% of the total) and methane (which represents 22.4% of the total).

The remaining emissions of nitrogen to the atmosphere are as other (i.e. non-greenhouse gas) air quality pollutants. These total 50.9 kt N / yr, split broadly evenly between nitrogen dioxide (NO2, 25 kt N / yr), mainly from combustion in transport, industry and wider energy use) and ammonia (NH3, 25.9 kt N / yr), mainly from agricultural sources. Compared with these total air quality pollutant emissions from Scotland's territory, it is also estimated that 64.2 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. 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.

Additional nitrogen inputs to semi-natural habitats from atmospheric deposition can cause substantial biodiversity effects, damaging sensitive vegetation and the wildlife dependent 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.

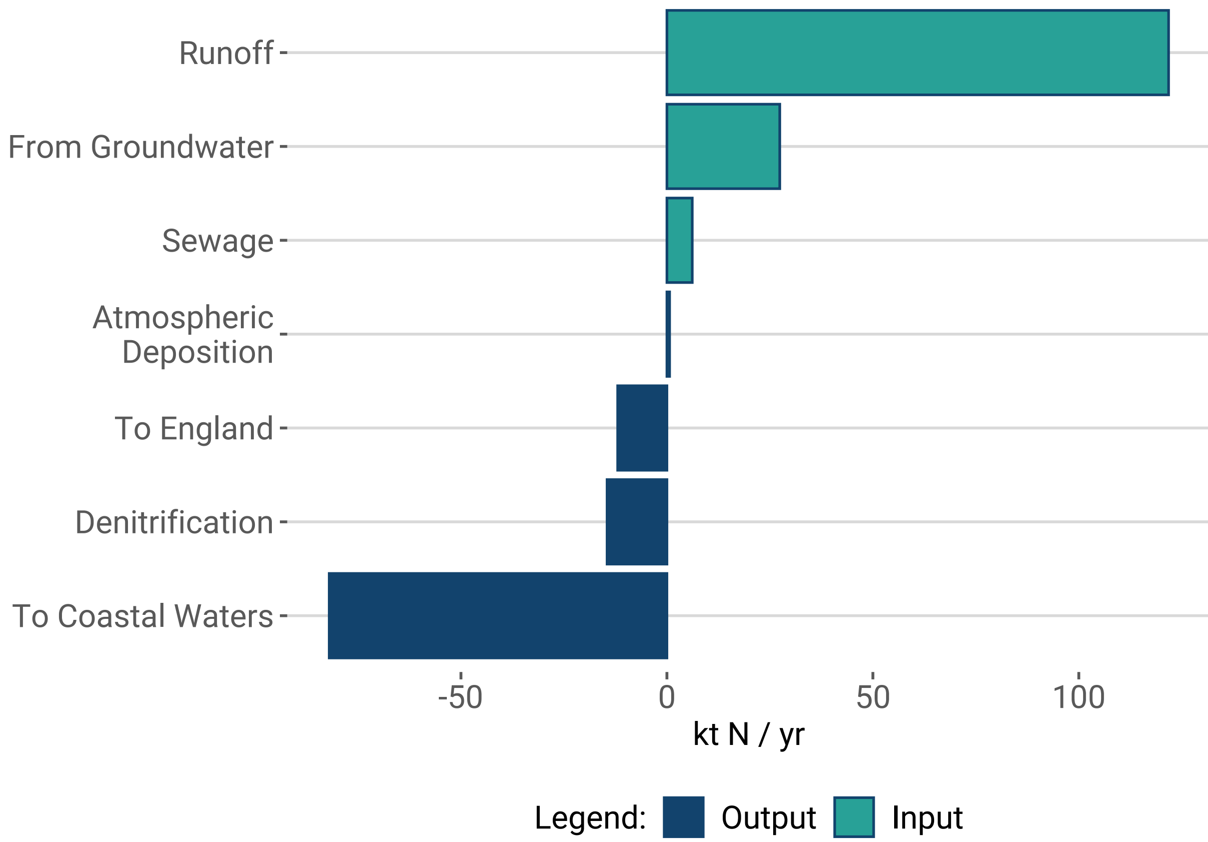
The spatial distribution of air pollutant emissions and atmospheric concentrations therefore matters in terms of where impacts occur. For nitrogen deposition, there are two main pathways, dry deposition (which occurs closer to the sources) and wet deposition (which can travel long distances, often hundreds 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 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, estimates can be made using existing scientific literature and expert knowledge. Overall, about 50.9 kt N / yr are estimated to be emitted as N_2 in Scotland, with 36.3 kt N / yr from terrestrial soils (including wetlands) and the remainder from hydrological systems.

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

Scotland's hydrosphere and aquatic (freshwater and coastal) ecosystems absorb and move nitrogen. The nitrogen mainly originates 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.

Figure 2 Flows of nitrogen into and from the hydrosphere. Values in kt N per year.



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 58.5 kt N / yr), arable (45.5 kt N / yr) and semi-natural habitats (17.8 kt N / yr from a combination of woodlands, heaths, grasslands, montane, etc.). Discharges from sewage processing and industrial sources contribute a further 6.1 kt N / yr.

These sources, combined with legacy nitrates in groundwater (mainly in some aquifers in eastern Scotland and estimated at 27.4 kt N / yr), together contribute to a total estimated discharge of nitrogen into Scottish coastal waters of around 155.3 kt N / yr. A further 15.4 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 13.8 kt N / yr.

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.

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 55.4 kt N / yr.

Figure 3 Flows of nitrogen into and from the animal husbandry sector. Values in kt N per year.

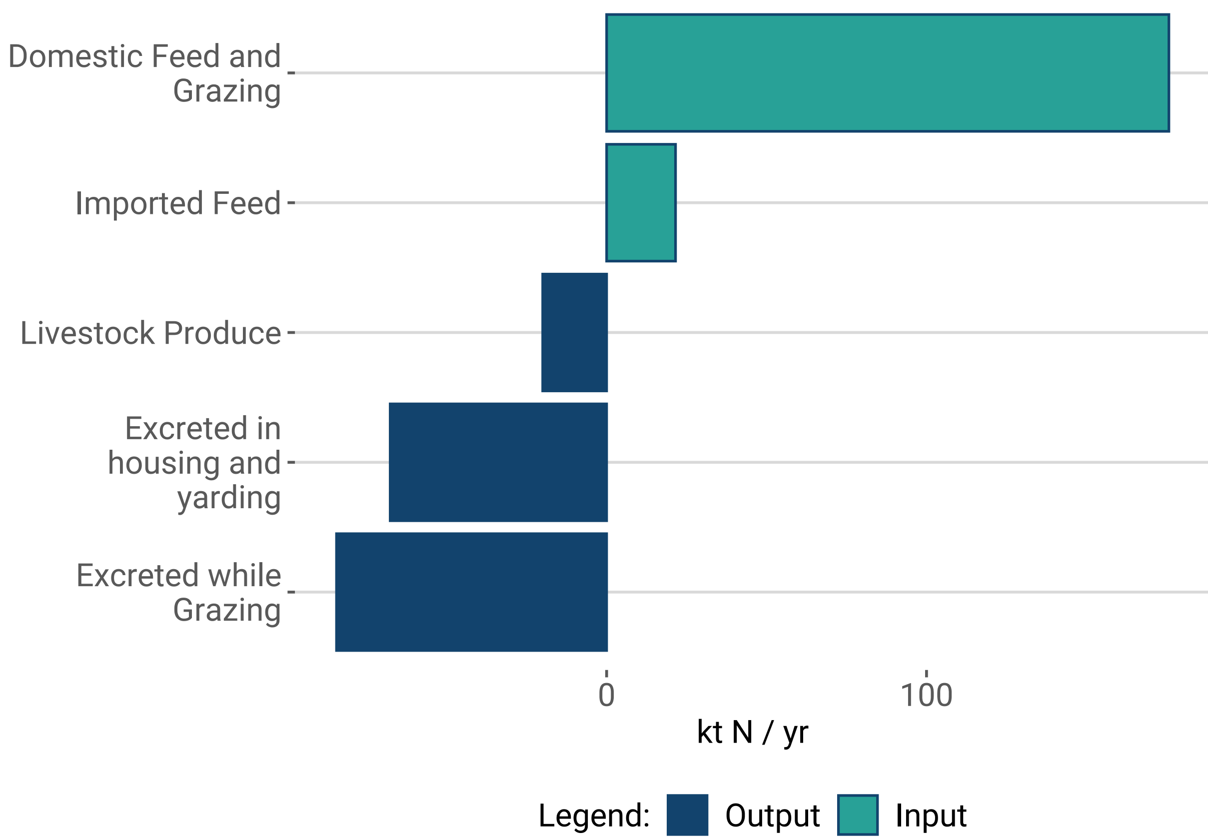
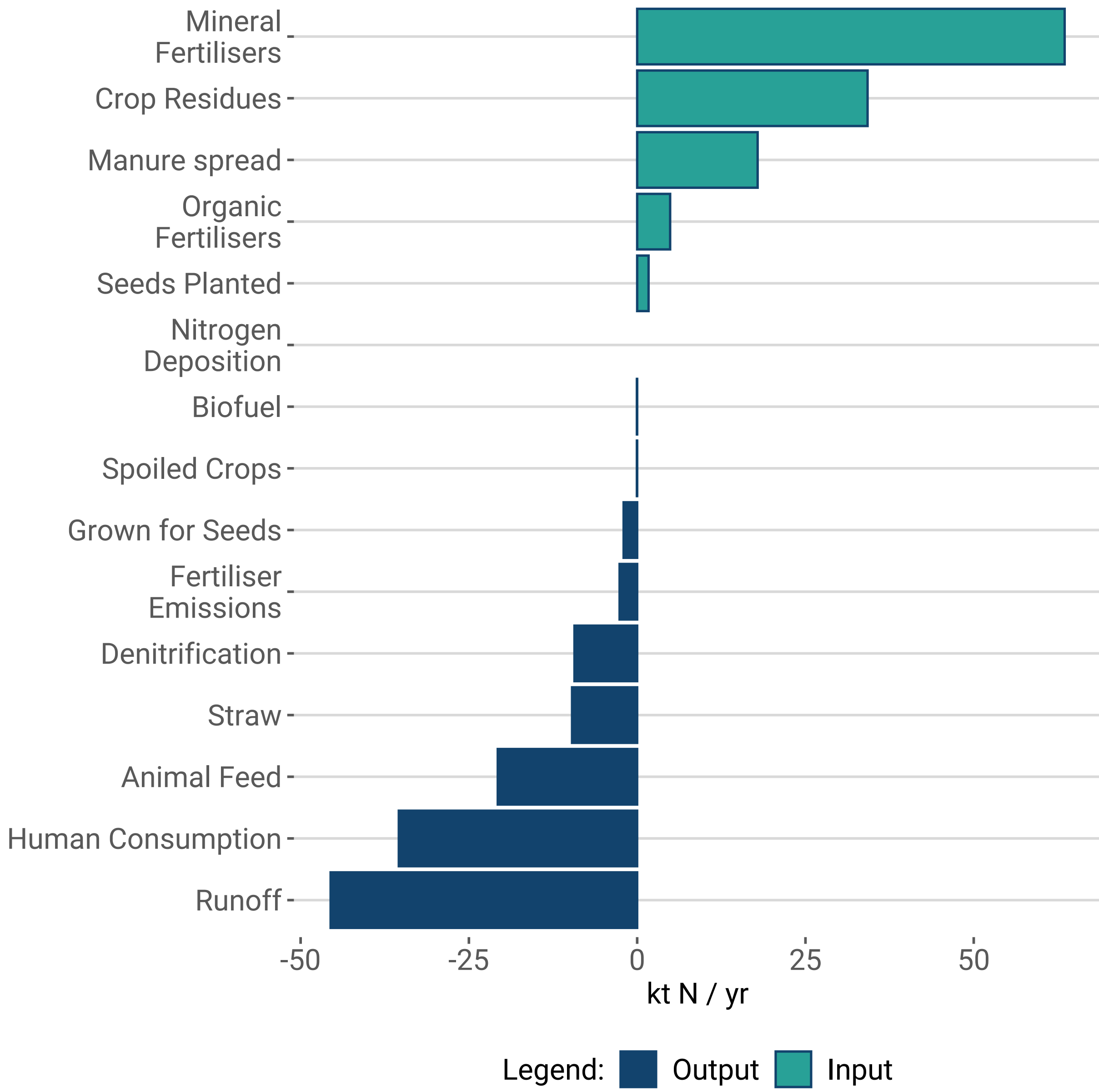


Figure 4 Flows of nitrogen into and from crop-based agriculture. Values in kt N per year.



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. These are predominantly of artificial origin with 130 kt N / yr of mineral fertilisers are applied compared to 9.8 kt N / yr of organic fertilisers

In addition to the anthropogenic inputs, 18.4 kt N / yr of biological nitrogen fixation through legumes occurs; 1.8 kt N / yr from peas and beans, and 16.6 kt N / yr from clover in grasslands. A further 12.1 kt N / yr is supplied by atmospheric deposition to agricultural areas.

Finally, an estimated 21.5 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 197.3 kt N / yr of nitrogen fed to animals.

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

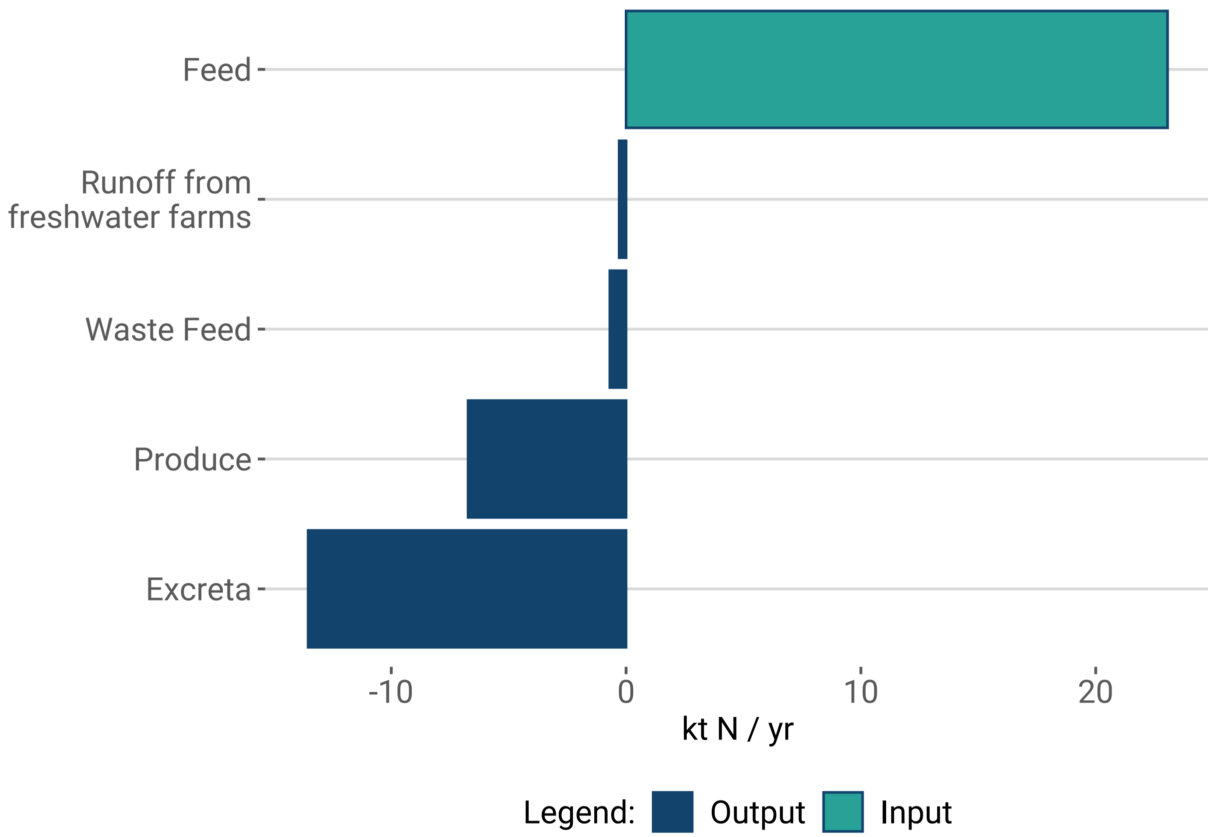
- emissions to the atmosphere, as the air quality pollutants ammonia (NH_3, emissions of 24 kt N / yr) and nitrogen dioxide (NO2, emissions of 1.2 kt N / yr) and as the greenhouse gas nitrous oxide (N2O, emissions of 5.5 kt N / yr).
- run-off and leaching from agricultural soils[3] to catchments and groundwater (flows of 104 kt N / yr, mainly as nitrates, but also dissolved organic and inorganic and particulate forms).

[3] There is further run-off and leaching from other land uses, such as forestry and terrestrial ecosystems

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.

Figure 5 Flows of nitrogen into and from fish farms. Values in kt N per year.

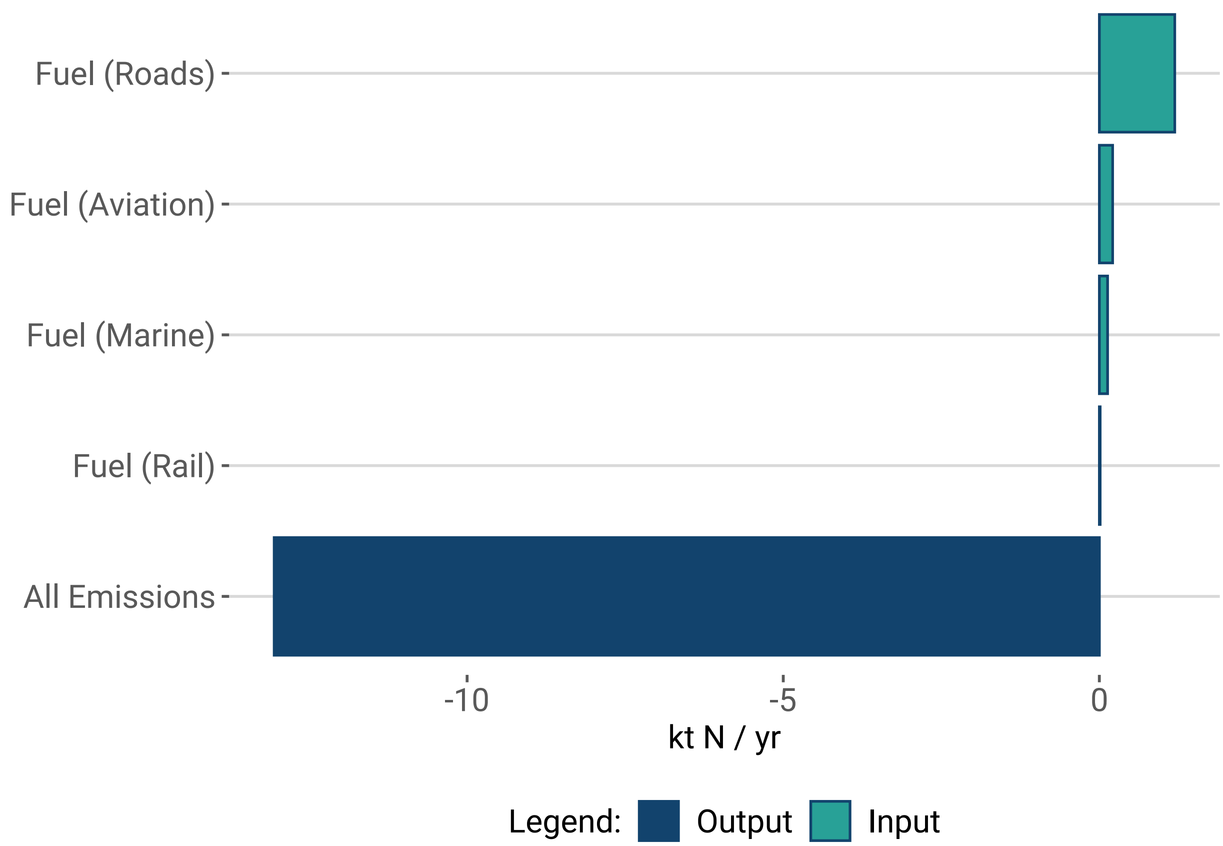


Useful outputs of nitrogen in harvested fish and shellfish produce are estimated at 6.9 kt N / yr, whereas the estimated anthropogenic input of feed into the system is at 23.1 kt N / yr. Losses of nitrogen into coastal waters are estimated at 14.5 kt N / yr, this being mostly in the form of nitrogen excreted by the fish, with only a small amount (estimated at 3%) of feed itself being lost.

Transport

Nitrogen's use in transport comes from its presence in the fossil fuels burnt by vehicles in Scotland. Most of this nitrogen is in the fossil fuels burnt by road vehicles (1.2 kt N /yr), which burn both petrol and diesel. Air transport (0.21 kt N /yr) and water transport (0.13 kt N /yr) are the next two largest users of nitrogen in transport. Rail transport uses the least amount of nitrogen (0.012 kt N /yr), mostly from diesel.

Figure 6 Flows of nitrogen into and from transport. Values in kt N per year.

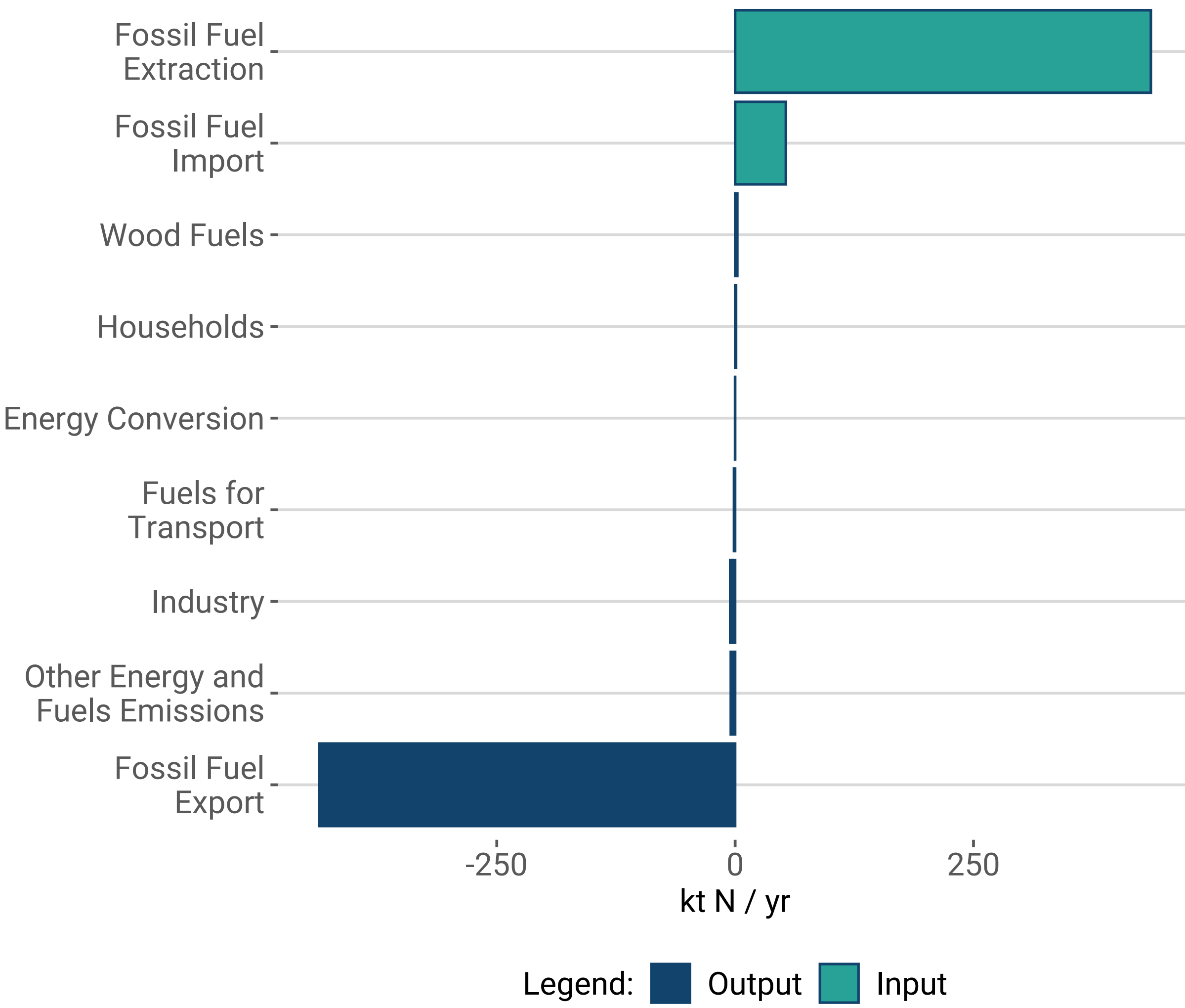


The key nitrogen flows from the transport sector are emissions to the atmosphere (13.1 kt N / yr), resulting from fuel combustion. The majority of these emissions are of air quality pollutants, mainly nitrogen dioxide (NO_2, emissions of 12.6 kt N / yr), and small amounts of ammonia (NH_3, emissions of 0.25 kt N / yr). Greenhouse gas emissions of nitrous oxide (N_2O) only amount to 0.2 kt N / yr, with the main climate effect from transport sources being due to emissions of CO_2.

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 11.3 kt N / yr.

Figure 7 Flows of nitrogen into and from the energy sector. Values in kt N per year.



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 0.19 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.

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 23.1 kt N / yr). There are also minor emissions to the atmosphere of ammonia (NH_3, emissions of around 1.2 kt N / yr in total).

Figure 8 Flows of nitrogen into and from the solid waste. Values in kt N per year.

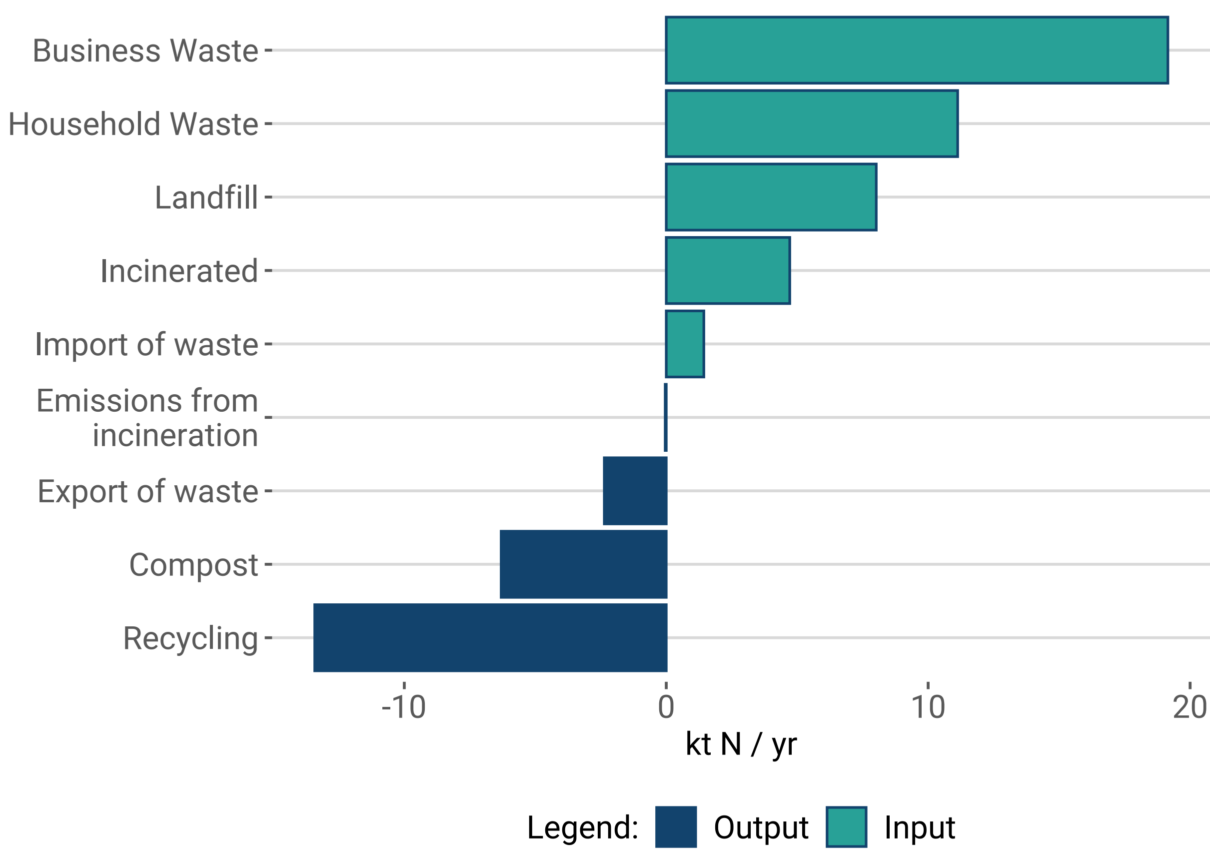
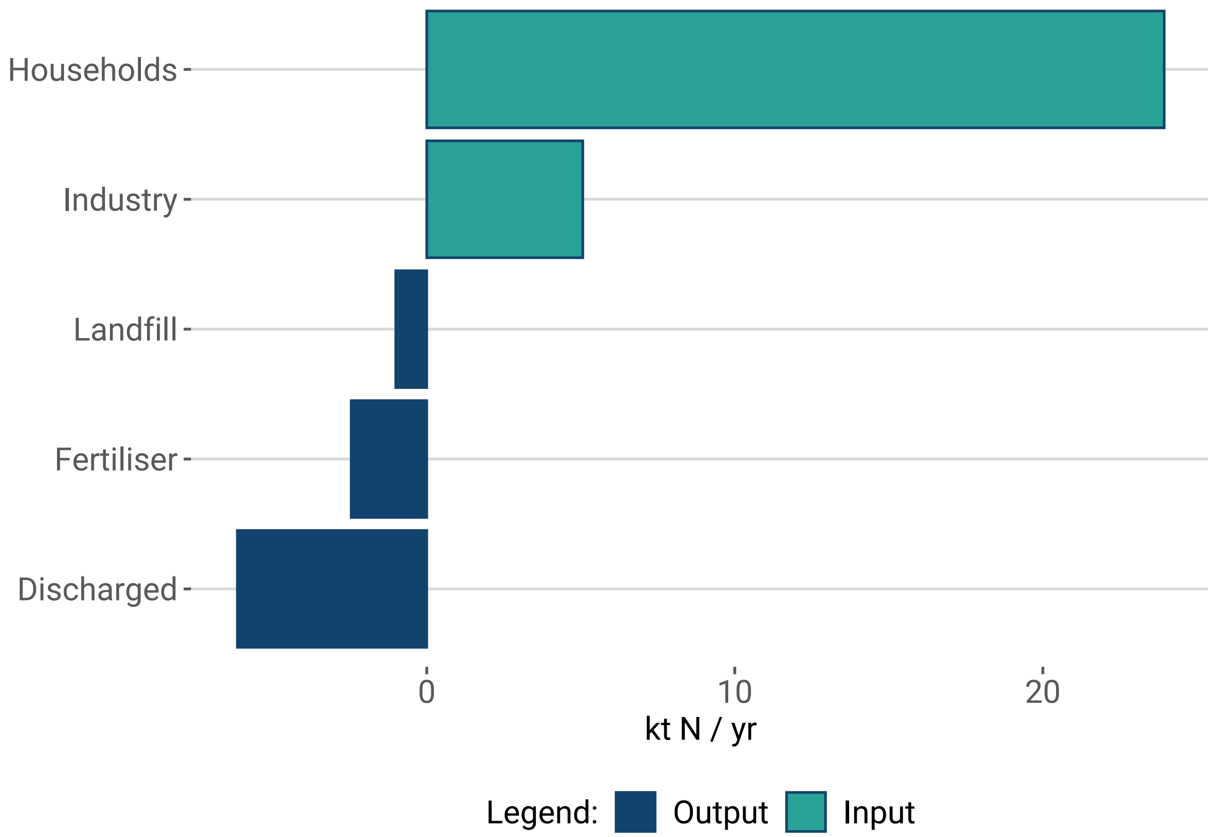


Figure 9 Flows of nitrogen into and from waste water. Values in kt N per year.



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 30.3 kt N / yr from household and business/industrial waste, plus the 23.1 kt N / yr of human excreta generated in Scotland (see above), it is estimated that around 13.1 kt N / yr are applied back to Scottish soils. A further 11.2 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 0.69 kt N / yr (mainly of ammonia and nitrous oxide).

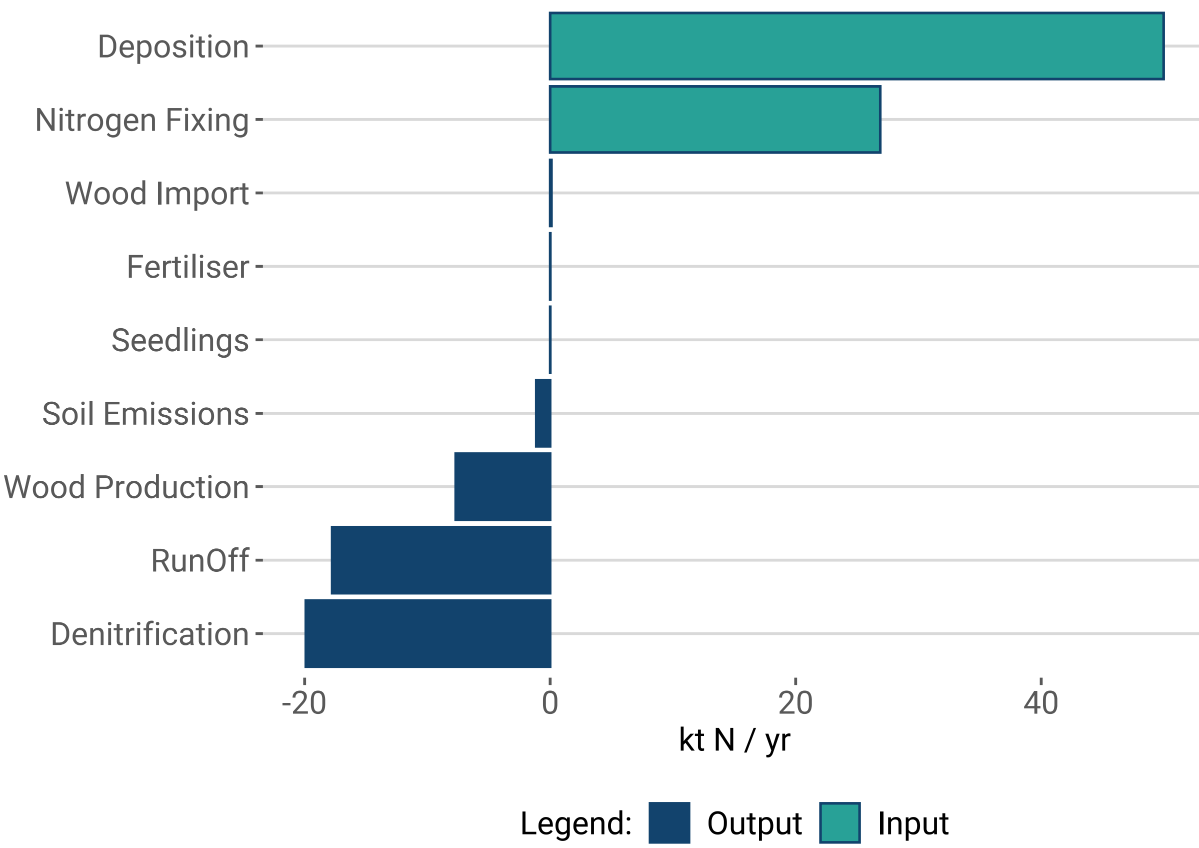
Other nitrogen associated with the waste sector is re-used within the Scottish economy (estimated at 13.4 kt N / yr) or buried in landfill sites (estimated at 8.7 kt N / yr).

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.

Figure 10 Flows of nitrogen into and from semi-natural environments. Values in kt N per year.



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 2020 was mostly destined for material (4.9 kt N / yr) and energetic (2.3 kt N / yr) uses, with a further 0.4 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 (10.9 kt N / yr) or nitrogen deposition from the atmosphere (17.1 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)[4].

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 32.8 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 17.8 kt N / yr)[5].

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

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

Nitrogen Use Efficiency

Overview

The Climate Change (Nitrogen Balance Sheet) (Scotland) Regulations 2022, requires the SNBS to provide the basis of a whole-economy calculation of Nitrogen Use Efficiency (NUE).

The section “Methodology for estimating Nitrogen Use Efficiency (NUE) metrics” sets out key elements of the methods used for this calculation. 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 the previous section.

In order to contextualise this analysis, which 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.

Crop production Nitrogen Use Efficiency

Table 1 Contributors to NUE in crop production

Inputs to arable land	kt N
mineral fertiliser (to arable/crops)	63.5
slurry/manure (to arable/crops)	17.9
atmospheric N deposition (to arable)	4.0
digestate (non-crop/crop waste feedstocks only) (data not available as split between arable/grass - using 50%)	2.0
seeds (sowing/planting)	1.7
biological N fixation (BNF) by arable crops	1.8
sewage sludge (data not split into arable/grass - using 50%)	1.2
compost (assumed to go to arable/horticulture)	0.89
Total	93.1

Useful outputs	kt N
harvest (as food, includes human-edible crops that end up as livestock feed, seed materials or biomass)	56.7
harvest (planted as fodder crops)	1.6
Total	58.2

Note: Recycling terms are not included in either inputs or outputs for the purpose of this NUE calculation: digestate from crops, crop residues.

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, 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 62.5%. This reflects 58.2 kt / yr of useful outputs produced, relative to 93.1 kt / yr of inputs (a full breakdown is provided in the above tables).

NUE = 58.2 ÷ 93.1 = 62.5%

The 62.5% figure compares well with international data published for 124 countries (up to 2009)[6], 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.

Livestock Feed Conversion Nitrogen Use Efficiency

Table 2 Contributors to NUE in Livestock Feed Conversion

Feed inputs to livestock	kt N
feed (includes grass, fodder crops, concentrates)	197.3
Total	197.3

Useful outputs	kt N
livestock produce (milk, eggs, meat, wool)	20.0
Total	20.0

Note: Recycling terms (not included in either inputs or outputs for the purpose of this NUE calculation): manures, materials used to grow the feed which is entangled with crop farming

Looking only at livestock's ability to turn feed (including grazing) into produce yields a NUE of around 10.1%, reflecting 20 kt N /yr of produce from 197.3 kt N /yr of feed.

NUE = 20 ÷ 197.3 = 10.1%

[6] 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.

Whole-agriculture Nitrogen Use Efficiency

Table 3 Contributors to whole-agriculture NUE

Inputs to whole agriculture	kt N
mineral fertiliser (to arable/crops and grass)	130.0
livestock feed (not grown on Scottish farms, e.g. soy)	21.5
biological N fixation (BNF) by arable crops and grass	18.4
atmospheric N deposition (to arable and grass)	12.1
sewage sludge to agricultural land	2.5
digestate (non-agricultural feedstocks only)	2.7
compost to agricultural land	0.89
seeds (sowing/planting - net import)	-0.32
Total	187.7

Useful outputs	kt N
harvest (as food, excludes human-edible crops that are used as livestock feed or for seed)	35.4
livestock produce (milk, eggs, meat, wool)	20.0
Total	55.4

Note: Recycling terms (not included in either inputs or outputs for the purpose of this NUE calculation): manures/slurries, digestate of agricultural origin, straw (comes back to fields via manures), fodder crops grown on farm

For mixed crop / livestock production systems, the output side of the NUE equation includes both livestock and crop produce. 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 29.5%. This reflects 55.4 kt N / yr of useful outputs produced, relative to 187.7 kt N / yr of inputs (a full breakdown is provided in the above tables, as part of a wider all-food-production analysis).

NUE = 55.4 ÷ 187.7 = 29.5%

The whole-agriculture NUE figure of 29.5% being so much lower than the figure for crop production alone (62.5%) 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.

As such, any country with an agriculture sector that contains a relatively large proportion of livestock 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. 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.

Aquaculture Nitrogen Use Efficiency

Table 4 Contributors to aquaculture NUE

Inputs to aquaculture	kt N
aquaculture feed	23.1
Total	23.1

Useful outputs	kt N
harvest (finfish coastal waters)	6.5
harvest (shellfish)	0.17
harvest (finfish freshwater)	0.2
Total	6.9

Note: Recycling terms (not included in either inputs or outputs for the purpose of this NUE calculation): assuming no harvested outputs from aquaculture produce are recycled into aquaculture feed.

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. 29.9%. This reflects useful output products of 6.9 kt N / yr, relative to inputs of 23.1 kt N / yr.

NUE = 6.9 ÷ 23.1 = 29.9%

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 (29.9%) than it is for agricultural livestock (10.1%), as fish are cold-blooded and a larger proportion of their feed is converted into protein.

All-food-production Nitrogen Use Efficiency

Table 5 Contributors to all-food-production NUE

Inputs to all food production	kt N
mineral fertiliser (to arable/crops and grass)	130.0
livestock feed (not grown on Scottish farms, e.g. soy)	21.5
aquaculture feed	23.1
biological N fixation (BNF) by arable crops and grass	18.4
atmospheric N deposition (to arable and grass)	12.1
sewage sludge to agricultural land	2.5
digestate (non-agricultural feedstocks only)	2.7
compost to agricultural land	0.89
seeds (sowing/planting - net import)	-0.32
Total	210.8

Useful outputs	kt N
harvest (as food, excludes human-edible crops that are used as livestock feed or for seed)	35.4
livestock produce (milk, eggs, meat, wool)	20.0
harvest (finfish coastal waters)	6.5
harvest (shellfish)	0.17
harvest (finfish freshwater)	0.2
Total	62.3

Note: Recycling terms (not included in either inputs or outputs for the purpose of this NUE calculation): manures/slurries, digestate of agricultural origin, straw (comes back to fields via manures), fodder crops grown on farm, assuming no harvested outputs are recycled into aquaculture feed (however modern fish feed contains plant ingredients, including some homegrown).

By combining the SNBS data across the agriculture and aquaculture sectors, a value for all-food-production NUE can be estimated as 29.6%. This reflects total useful outputs of 62.3 kt N / yr, relative to total inputs of 210.8 kt N / yr (a full breakdown is provided in the above tables).

NUE = 62.3 ÷ 210.8 = 29.6%

The all-food-production NUE figure is dominated by the much larger overall magnitude contribution from agriculture (with an estimated NUE of 29.5%), slightly increased by the contribution from aquaculture (with an estimated NUE of 29.9%).

Forestry NUE

Forestry is the only non-food related sector producing a significant amount of useful outputs from which a NUE can be calculated.

Table 6 Contributors to Forestry NUE

Inputs to forestry	**kt N**
atmospheric N deposition to woodland	17.1
biological N fixation (BNF) by forests	10.9
import of wood	0.11
mineral fertiliser to woodland planting	0.016
seedlings (planting)	0.013
Total	28.2

Useful outputs	**kt N**
Forestry harvest - material use	4.9
Forestry harvest - wood fuel	2.3
Forestry harvest - export	0.45
Total	7.7

Inputs to forestry are primarily from the trees and the woodland they are in more generally absorbing nitrogen from the atmosphere, for a total of 28.2 kt N /yr. Outputs are the wood harvested for material use, fuel and export, which totals 7.7 kt N /yr. This produces a NUE of 27.3%

NUE = 7.7 ÷ 28.2 = 27.3%

N.B. Forestry NUE is not all that useful, as much of forest N is locked up in stocks/standing forests. NUE could be increased by depleting stocks (i.e. increased felling), which is not a useful concept. That the anthropogenic inputs (fertiliser and seedlings) represent such a small proportion of the inputs to forestry further limits the utility of this measure.

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.

Table 7 Contributors to Whole Economy NUE

Inputs at whole economy level	kt N
mineral fertiliser (all land)	130.0
biological N fixation (all land)	45.3
atmospheric N deposition (imported NO_x + NH_x only)	38.3
emissions from fuel burnt in Scotland (to account for transport, energy & industry)	24.6
livestock feed (not grown in Scotland)	21.5
aquaculture feed	23.1
import: fish landings	8.0
import of wood (roundwood)	0.11
seeds (sowing/planting - net import)	-0.32
import: consumer goods, food etc	0.0
Total	290.6

Useful outputs	kt N
harvest (as food, excludes human-edible crops that are used as livestock feed or for seed)	35.4
livestock produce (milk, eggs, meat, wool)	20.0
import: fish landings	8.0
Forestry harvest - all uses (inc. export)	7.7
aquaculture produce (finfish freshwater, coastal))	6.9
exported materials (that aren’t already accounted for above) - e.g. industrial output	0.0
Total	78.1

Note: Recycling terms (not included in either inputs or outputs for the purpose of this NUE calculation): manures/slurries, other recycled materials (composts, sewage, digestate), straw (comes back to fields via manures), assuming no harvested outputs are recycled into aquaculture feed (however modern fish feed contains plant ingredients, including some homegrown), N deposition originating from Scottish ammonia and NO_x emissions, all livestock feed grown in Scotland (grass and fodder), seeds/planting materials grown in Scotland

The estimated value of the figure for economy-wide NUE is 26.9%. This reflects total useful outputs of 78.1 kt N / yr, relative to total inputs of 290.6 kt N / yr (a full breakdown is provided in the above tables).

NUE = 78.1 ÷ 290.6 = 26.9%

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.

The economy-wide NUE figure for Scotland of 26.9% is dominated by the NUE value associated with food production (of 29.6%).

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 NO_x emissions from fuel burnt in Scotland and are statutorily required to be taken into account for the whole-economy NUE metric; and have been done so on the basis proposed by the OECD[7].
- 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 the methodology subsection "Methodology for estimating Nitrogen Use Efficiency (NUE) metrics".

Comparison to 2019

Table 8 Comparison between 2019 and 2020 NUE figures.

	Nitrogen input 2019 (kt N /yr)	**Useful nitrogen output 2019 (kt N / yr)**	**Nitrogen use efficiency 2019**	**Nitrogen input 2020 (kt N /yr)**	**Useful nitrogen output 2020 (kt N /yr)**	**Nitrogen use efficiency 2020**
Arable	90.2	58.2	64.6%	93.1	58.2	62.5%
Livestock	198.7	19.6	9.9%	197.3	20.0	10.1%
All Agriculture	200.1	54.5	27.2%	187.7	55.4	29.5%
Aquaculture	21.3	7.3	34.3%	23.1	6.9	29.9%
All Food	221.4	61.8	27.9%	210.8	62.3	29.6%
Forestry	28.2	7.5	26.6%	28.2	7.7	27.3%
Whole Economy	**308.2**	**77.7**	**25.2%**	**290.6**	**78.1**	26.9**%**

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

Compared to 2019, the whole economy NUE is slightly higher, driven by both a decrease in measured inputs and a slight increase in measured useful outputs.

Looking at all agriculture, an increase in efficiency from 27.2% to 29.5% is shown between 2019 and 2020. This is primarily due to a reduction in the overall amount of mineral fertiliser required, but it is not apparent from the sub-categories of agriculture that this overall increase in efficiency should be seen. However, as noted under table 3, there are some recycling terms. For example, some of the crops grown by arable agriculture are destined for use as animal feed and so are netted-out when considered across all agriculture.

Caution should be taken when comparing NUE values from year to year. The SNBS is a relatively new publication and there are still further improvements to be made with data sources. The filling in of any gaps in either the measured inputs or measured outputs would result in either a decrease or increase in the NUE. Methodology related changes in the NUE may also be seen when switching sources to sources more suitable for yearly updates. See sections Revisions and Next Steps for changes to the data for this release and planned changes in future releases.

Methodology

Summary of technical approach

The technical approach builds from work set out in a previous technical study undertaken by the UK Centre for Ecology & Hydrology for SEPA in 2019[8]. That study made a limited, first attempt at a national Nitrogen Balance Sheet for Scotland, but with several substantial data gaps. The current SNBS builds from this, in particular by seeking to fill data gaps, broaden scope and adapt the methods to be compatible with international guidelines. 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 = Useful N Outputs ÷ N inputs × 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

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[8] A nitrogen budget for Scotland (2019) UKCEH report to SEPA

undertaken for the SNBS and summarised in the Nitrogen Use Efficiency section of this report have been undertaken in line with a 2013 OECD paper[9] and other relevant international guidance on methodology (e.g. as available from the UN Economic Commission for Europe and the EU Nitrogen Expert Panel)[10].

The SNBS draws on the latest published Official Statistics and other data sources that were available as of publication. This means that the majority of the data relates to nitrogen flows for the calendar year 2020, 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 publication, 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 previous versions of the SNBS.

Data Sources

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]

The data underpinning the agricultural 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[14] (which is based on a wide range of Official Scottish statistics for 2019), hydrological modelling commissioned by SG from UKCEH[15]

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

[10] EU Nitrogen Expert Panel web pages

[11] Regional freshwater nitrogen budgets for Scotland - NERC Open Research Archive

[12] SPRI | Scottish Environment Protection Agency (SEPA)

[13] Scotland's Aquaculture | Home

[14] NAEI, UK National Atmospheric Emissions Inventory - NAEI, UK (beis.gov.uk)

[15] Regional freshwater nitrogen budgets for Scotland - NERC Open Research Archive

(2010 data), other Official Statistics (including the Scottish Agricultural Census[16]) and expert advice from researchers at e.g. SRUC and UKCEH.

The methodology for estimating the aquaculture nitrogen flows matches used by SEPA for regulatory purposes[17] 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.

The transport emission figures are taken directly from the UK's air pollutant and GHG emission inventories. The road fuel consumption figures are based on Scottish Transport Statistics[18], the rail fuel consumption figures are based on BEIS figures[19].

The industry and energy emissions data 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.

All atmospheric emissions data for the humans and settlements 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. Protein intake figures are based on National Records of Scotland population estimates combined with average protein intakes per individual.

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[21] was developed by the UN ECE Task Force on Reactive Nitrogen's Expert Panel on Nitrogen Budgets[22] and contains detailed draft annexes outlining the recommended methodology[23]. This guidance builds on existing national data collections wherever

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[16] Results from the Scottish Agricultural Census: June 2021

[17] Materials to land in the circular economy (sepa.org.uk)

[18] Scottish Transport Statistics No. 39 2020 Edition

[19] UK road transport energy consumption at regional and local authority level, 2005 to 2020

[20] Scottish energy statistics hub index - gov.scot (www.gov.scot)

[21] United Nations (clrtap-tfrn.org)

[22] UN ECE Task Force on Reactive Nitrogen (TFRN): Expert Panel on Nitrogen Budgets (EPNB) webpages

[23] UN ECE (2021) Guidance document on national nitrogen budgets: draft detailed annexes.

possible, including the international greenhouse gas and air quality pollutant emission inventory reporting mechanisms and the OECD/EUROSTAT methodology[24] 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[25].

The SNBS 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. 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. 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)[26]. For example, ammonia (NH_3) consists of one molecule of Nitrogen and 3 molecules of Hydrogen, therefore the total molecular weight of NH_3 = 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 the Nitrogen Use Efficiency section 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.

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[24] European Commission EUROSTAT (2013) Methodology and Handbook Eurostat/OECD Nutrient Budgets.

[25] Reactive nitrogen flows in Germany 2010 - 2014 (2020) report

[26] Also referred to as atomic number – see for example Periodic Table of Elements - PubChem (nih.gov): select "atomic number" as display property

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 the section on Nitrogen Use Efficiencies, alongside the calculations. 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.

Revisions

The main difference between the initial publication of the SNBS and this release has been to translate the calculations onto a new software platform in order to enhance transparency and to encourage further development.

Next Steps

There are two main areas for improvement in the SNBS. The first area relates to consistency by identifying replacements or proxies for some data sources which lack annual updates. The second direction relates to completeness; filling in the remaining data gaps in the SNBS which are currently not estimated.

Annual Updates to All Data Sources

Not all of the data sources used for this edition of the SNBS relate to 2020, because some data sources lack annual updates. One reason for this can be that they are the result of one-off or infrequent modelling. Another reason can be that some updates to the data source are missing a time period due to the pandemic or other interruptions.

It is our current intention within the next five years to have some form of annual update available to all of the source data for the SNBS, whether this be due to (in order of preference) direct measurement as a result of new data collections, modelling, or estimations based on some proxy measurement.

Summary of current data gaps for the SNBS

The main remaining data gaps in the SNBS 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[27] 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 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 semi-natural area cases covered, 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:

- Agriculture livestock feed conversion calculations: The calculations applied are based on work by SRUC[28] and its representation in Scotland's Material Flow Accounts (MFA)[29]. 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 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.

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

[28] 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.

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

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The data collected for this statistical bulletin are available in the supporting files section accompanying this release.

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