A Nitrogen Budget for Scotland

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Contents

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Abstract

The aim of this study was to quantify key nitrogen flows for Scotland, bringing together the most recent available data for soils, water, air and human consumption/production (with an emphasis on agriculture, nutrition and waste). Losses of N to water (132 kt N yr^{-1}), air (80 kt N yr^{-1}) and terrestrial systems (90 kt N through atmospheric deposition) estimated here are substantial, and these are mainly due to agricultural activities and, to a smaller extent, waste recycling/processing. Improved nutrient use efficiency is critical for delivering both environmental and economic benefits. However, further work is required to complete currently unquantified and uncertain flows and provide more detail on key activities, to enable the development of policy options, in conjunction with SEPA's Sector Plans.

1. Introduction

This short project aimed to develop a Nitrogen (N) budget for Scotland by quantifying key N flows across the atmosphere, hydrosphere, terrestrial systems (agricultural and semi-natural) as well as transport, industry and human consumption and waste sectors. The main objective was to provide an overview of the current state of knowledge and relative size of the various nitrogen-based flows in Scotland, and to suggest further research for refining the quantification of budget terms and/or expand the level of detail subsequently, as needed. The study was commissioned to assist SEPA with their developing sector plans, for identifying those budget terms where effective mitigation and improved nutrient use efficiency (NUE) are likely to improve environmental issues while supporting a sustainable economy. For example, the Crop Production sector plan[1] aims to drive towards recirculating nutrients from a range of sources (e.g. slurry, compost, treated sewage and digestate), to underpin long-term sustainable crop production in Scotland, improve farm business security and deal with water quality problems at source.

[1] https://consultation.sepa.org.uk/sector-plan/crop-production/

One of the first N budgets for the UK was provided by Leip et al. (2011), as part of the European Nitrogen Assessment (ENA, 2011). This combined N budget for atmosphere, agriculture and surface waters for the first time, for the period 1995 to 2008 (depending on data availability timeframes). The budget includes reactive N forms such as ammonia (NH_3), nitrogen oxides (NO_x), nitrates as well as the greenhouse gas N_2O, and aimed to include/discuss all main budget terms used by Leip et al. (2011), presented in a summarized format. Detailed numbers are provided in a separate spreadsheet (Annex A).

2. Methods

The study was carried out through a focussed literature and data review of available evidence on N flows in Scotland, to enable the development of a summary N budget from the current state of knowledge and determine the relative size of the main budget terms and flows. Given the project resources and timescale, the study is necessarily incomplete, and recommendations for further detailed work are given in Section 4.3.

The following methodology sections briefly describe and reference readily available methods and data sources that were used to estimate a first N budget for Scotland, for the atmosphere, hydrosphere/soils, and human consumption/production (including agriculture, industry, waste processing etc.).

2.1 Atmosphere

Atmospheric emissions

For emissions to air/gaseous losses from the agriculture, transport, industry, household and energy sectors, data were retrieved from the UK National Atmospheric Emission Inventory (NAEI, www.beis.naei.gov.uk). Data included in the budget were taken from the 2016 Air Quality Pollutant Inventories for NH_3 and NO_x and the 2016 Greenhouse Gas Inventories for N_2O. Additional data of NH_3 emissions from landspreading of anaerobic digestate and on-site processes at AD plants come from Tomlinson et al. (2017). In addition, emissions of N_2 and soil NO, which are not currently included in the UK emission inventories, were briefly assessed. Both gases are produced by the same processes that lead to N_2O production and emission, and therefore also respond to the rate of nitrogen input and availability. Dinitrogen (N_2) is an inert gas and emitted as part of the denitrification, often at rates 10 times larger than that of N_2O (Zaehle, 2013). As N_2 can only be measured using isotopic tracers, its emission rates are highly uncertain. Emissions of NO from soils are very small compared to combustion emissions, however in remote areas, agricultural derived NO emissions can be the main local source of raised atmospheric ozone concentrations, impacting human health and crop yields (Almaraz et al. 2018). Some of these terms have not been quantified for Scotland (or the UK) yet, and further work would be needed, beyond the resources of this pilot study.

Atmospheric deposition & source attribution

The Fine Resolution Multi-pollutant Exchange (FRAME) model (e.g. Dore et al. 2012) was used to estimate the origin of N deposited to land in Scotland. FRAME is a Lagrangian atmospheric transport model used to assess the annual mean deposition of reduced and oxidised N and sulphur over the United Kingdom. To estimate the contribution of individual emission source sectors (source attribution modelling), the FRAME model was run for a base scenario (all sources), then run again omitting each source or source sector in turn. The differences between the source-specific runs and the base run provides each source's footprint (see Bealey and Dore 2017). The resulting footprints can then be used to assess the relative contribution of the UK's countries, selected large point sources, international land-based sources and international shipping to N deposition received by Scotland, separately for reduced and oxidised N as well as dry vs wet deposition.

The absolute contribution from each UK country was then estimated using model output from the Concentration Based Estimated Deposition (CBED) model (for details on the model see Smith et al. 2000). The CBED model provides gridded (5 km by 5 km resolution) estimates of wet and dry deposition, based on measured concentrations of gases and particulate matter in air and measured concentrations of ions in precipitation. A 3-year average estimate of deposition for 2013-2015 (Smith et al. 2018) was used to remove inter-annual variability associated with variations in annual weather patterns. This has been demonstrated to be a suitable time period to smooth out some of the inter-annual variations in atmospheric N deposition. Estimates of N deposition outside of the UK landmass have not been quantified here, as this would require additional modelling to determine the contribution from Scottish sources.

2.2 Hydrosphere/soils

Water quality of rivers and lakes, as a spatial integrator of upstream nutrient sources, provides a way of assessing how the balance of many biogeochemical processes (in soils, agriculture, rivers, lakes) accentuates or mitigates against rising N loads to/in our freshwater systems and the coastal zone. A key difference between the approaches presented below is type of N quantified, with some focusing on nitrates only, and others including other types of N such as ammonium, DON etc.

Method 1 – Leip et al. (2011)

Leip et al. (2011) include both nitrate and ammonium N in waters. Although this N budget was not disaggregated into UK regions, indicative values for Scotland can be derived from the UK estimates by scaling by area and resident population figures (Table 1).

Method 2 – LTLS-IM

A second method to derive a N budget for Scotland is that developed by the LTLS (Long Term Large Scale: http://www.ltls.org.uk) consortium, funded under the NERC Macronutrient Cycles Programme. This comprised a national-scale integrated model (LTLS-IM) of the fluxes and stores of nutrients in the landscape at a 5 km by 5 km grid resolution, validated using long term (up to 100 years) N observations from across the UK. The LTLS-IM provides a national-scale modelling environment that combines simple process-based models for nutrient deposition (Tipping et al., 2017), runoff from semi-natural land (Davies et al., 2016a, b), agriculture (Muhammed et al., 2018), human waste (Naden et al., 2016) and water quality (Bell et al., 2019). The component models use readily-available driving data (climate, deposition, land cover, agricultural practices, topography) to reflect the heterogeneous response of the national landscape. The disadvantage of using a large-scale model that is not calibrated specifically to local conditions, is that it may be less accurate at the local scale (e.g. for a particular river) than a fully-calibrated site or catchmentspecific water quality model. However, it provides spatially consistent estimates of freshwater nutrient sources and fluxes across Scotland and takes account of longer-term nutrient fluxes including groundwater. Results are based on 2010 model output.

Method 3 – NIRAMS[2] model

The Nitrogen Risk Assessment Model for Scotland (NIRAMS; Dunn et al. 2004a, 2004b) is a spatially distributed model that quantifies agricultural N exports (nitrate only) to surface and ground waters. Nitrate leaching is simulated for 1 km × 1 km grid cells based on climatic variables, inorganic fertiliser and manure inputs, and land use and soil characteristics. The model includes mineralisation, denitrification, and leaching. The original NIRAMS model is very complex and its use is limited by the very long computational times associated with estimating uncertainty based on multiple parameter sets, and for simulating the effects of multiple change scenarios based on climate and land management.

More recently, a computationally efficient Gaussian process emulator has been developed for the model that works under baseline conditions (2010-2015, observed climate and land management as per the agricultural census) and for various climate and land management scenarios, using 81 parameter sets in each case. Model outputs include average nitrate concentrations in individual grid cells and groundwater bodies, and the frequency of threshold exceedances.

Method 4 – Gooday et al (2016)[3]

Gooday et al. (2016) used a computer model to calculate diffuse N emissions to air and water from land, urban areas and point source discharges for Scotland. The model was adapted to partition total N emissions for agricultural source types and areas, and via the delivery pathways found on farms. The simulations were carried out for by farm type on a 1 km x 1 km grid, using local soil and climate information. The model is based on an export coefficients approach that expresses modelled N emissions as a linear function of the potential N input to farms as fertiliser and livestock excreta. In contrast to typical export coefficient models, however, N emissions were also expressed as a function of area for pollutant sources that are intrinsic or respond slowly to reducing inputs, e.g. nitrate emissions from background soil organic nitrogen supply. Non-agricultural pollutant losses were calculated for each Water Framework Directive (WFD) river water body based on tabulated discharges and empirical models, e.g. for urban run-off, and N emissions from other non-agricultural areas were calculated from atmospheric N deposition and land cover. Point source emissions were calculated separately for septic tanks and sewage treatment works.

Method 5 – SAGIS

The Source Apportionment-GIS (SAGIS) Tool apportions loads and concentration of chemicals, including N, to WFD water bodies and was originally developed to support river basin planning by the UK Water Industry and the Environment Agency for effective implementation of

[2] https://www.hutton.ac.uk/research/developing-gaussian-process-emulator-nitrogen-risk-assessment-model-scotland-nirams

[3] Data available from https://data.gov.uk/dataset/1c0c8eca-066e-4068-b67f-931c7937e315/non-agricultural-pollution-to-rivers-in-scotland and https://data.gov.uk/dataset/036b5bf2-2977-47ed-b51a-e734bbc7b71d/diffuse-agricultural-pollution-to-rivers-in-scotland.

programmes of measures. The Tool quantifies the loads of pollutants to surface waters from 12 point and diffuse sources, including wastewater treatment works discharges, intermittent discharges from sewerage and runoff, agriculture, soil erosion, mine water drainage, septic tanks and industrial inputs. As inputs, the model requires diffuse inflow (derived from Lowflows 2000) at waterbody scale, diffuse outputs of N from the NEAP N model, observed effluent and rivers flows and water quality, and GIS data for rivers, lakes, estuaries, waterbodies and location of point sources. SAGIS outputs simulated river flow and water quality data as concentrations and loads and spatial information on lake volume, lake outflow, water quality concentrations and annual mean and percentile statistics. When run at national scale, the input loads to each of the 2700+ waterbodies are summed to give an overall load for each input sector.

2.3. Human consumption and production

Crop and livestock production

The N content of agricultural livestock feed and excreta applied to soil in Scotland were taken from Leinonen et al. (2019). Other datasets and methods of calculation are available, including the use of data from the UK agricultural emission inventory database (Defra project SCF0107, Wakeling et al. 2018) which provides the estimate for N content of fertilisers applied to soil.

Human Consumption

Protein intake by gender and age for the UK was retrieved from the National Diet and Nutrition Survey (Whitton et al., 2011) and converted to N intake using a factor of 16% protein N content. Age and gender specific N intakes were then multiplied by Scottish demographic data (NRS, 2017) to give an overall total N intake for Scotland.

3. Results

3.1 Hydrosphere/soils

N inputs to/from water

A summary of N fluxes to and from water bodies from the approaches laid out in Section 2.2. is provided in Table 1. Key differences are due to different parts of the N budget included – with Gooday et al. (2016) and NIRAMS focusing on nitrate, while LTLS-IM and Leip et al. (2011) include N forms other than nitrate derived inputs to water. LTLS-IM provides the most complete N budget, with output consisting of dissolved and particulate phases:

- Dissolved: nitrate-N (NO_3-N), ammonium-N (NH_4-N) and dissolved organic nitrogen (DON)
- Particulate: labile (PONL) and non-labile (PONNL) nitrogen.

The total sum of N sources from Leip et al. (2011) and LTLS-IM are remarkably similar (160 kt vs 159 kt N), given the differences in the methodology. The differences between the nitrate estimates by Gooday et al. (2016) and NIRAMS are mainly due to different methods used for calculating N losses from sewage sources. In addition, the nitrate losses from agriculture by the NIRAMS Tool were found to be 25% lower than calculated by Gooday et al. (2016).

Table1. Comparison of nitrogen sources (kt N y^{-1}) to water in Scotland, as calculated by LTLS-IM, values derived for Scotland from Leip et al. (2011)'s UK budget and values modelled by Gooday et al. (2016), NIRAMS and SAGIS.

Source	LTLS-IM (kT N y^{-1})	Leip et al. (2011) (kT N y^{-1})	Gooday et al. (2016) (kT N y^{-1})	NIRAMS (kT N y^{-1})	SAGIS (kT N y^{-1})
Agriculture	105	128[1]	60.7[3]	46.3[3]	40.2[3]
Semi-natural	18	16[2]	5.8[3]		
Sewage + septic tanks	9	16[2]	5.1[3]	12.5[3]	6.8[3]
Stored groundwater	27	N/A	N/A	N/A	N/A
Other (e.g. urban run-off)	<1	N/A	1.7[3]	3.2[3]	1.4[3]
TOTAL flux to water	159	160[1,2]	73.3[3]	62.0[3]	48.4[3]

[1] Based on values for Scotland presented in Fernall and Murray (2009)
[2] UK values in Leip et al. (2011) scaled by area of Scotland, assuming 73% of land is in agricultural production and a human population of 5 million.
[3] Nitrate only.

A key advance due to the LTLS-IM work is on N in groundwater over longer time periods. Groundwater N stored in the unsaturated zone is predominantly derived from leaching from agricultural soils, but can also be from animal and human wastes, septic systems and from atmospheric deposition. Wang et al. (2013) quantify the temporal delay in nitrate concentrations in the water table. In Scotland, the delay in nitrate travel times is between 0 and 50 years, and typically less than 10 years in lowland areas. The figure of 27 kt N in Figure 1 reflects nitrate leaching from soils that has been stored in groundwater across Scotland over previous decades before it is released to river and subsurface flows.

Export by rivers to the sea

We focus on outputs by LTLS-IM here, as the most complete approach in terms of forms of N considered, with comparisons to other methods where relevant. Runoff and leaching of dissolved and particulate N from soils and sewage are assumed to travel laterally with water across the landscape in subsurface and fluvial flow pathways to the sea. LTLS-IM estimates nutrient biogeochemistry parameters (primary production, organic matter decomposition, nitrifying activity and oxygen balance) in rivers and lakes. Both dissolved and particulate nutrient processes are simulated, and while nutrients are conserved though the routing scheme, losses to the river system (Bell et al. 2019) and lakes (Tipping et al. 2016) though storage in river sediments, denitrification and decomposition are included. Figure 1 indicates a flux of N gas of 17 kt N from rivers and lakes to the atmosphere by denitrification.

The total flux of N to the sea in dissolved and particulate form by LTLS-IM is estimated as 142 kt N in 2010. This flux can be broken down into the fluvial flux (~88 kt) and the subsurface, or groundwater flux to sea (~54 kt). By comparison, the total fluvial flux of Nitrate and Ammonium measured at HMS sites in 2010 across Scotland is 51 kt, and excludes N in the form of DON, and particulate nitrogen. Observations of nutrient fluxes based on measurements from HMS sites reflect only ~60% of catchments across Scotland, thus the estimate of 88 kt N of coastal flux from all rivers across Scotland seems reasonable. The direct leakage of groundwater N to coastal waters can be significant but is often neglected as it can be challenging to quantify. Lewandowski et al. (2013) suggest that the total flux of SGD (Submarine Groundwater Discharge) to the Atlantic Ocean is similar in volume to the amount of riverine discharge into the ocean. Beusen et al. (2013) found that global SGD transport to coastal waters increased from 1.0 to 1.4 Tg of nitrate (NO_3-N) per year between 1950 and 2000 and expected an increase of another 20% in the following decades. In the N budget for Scotland estimated here using the LTLS-IM, which assumes a long-term balance between terrestrial inputs and losses to coastal waters and atmosphere, the total flux of N in SGD to coastal waters was estimated as 54 kt in 2010 (Bell et al. 2019).

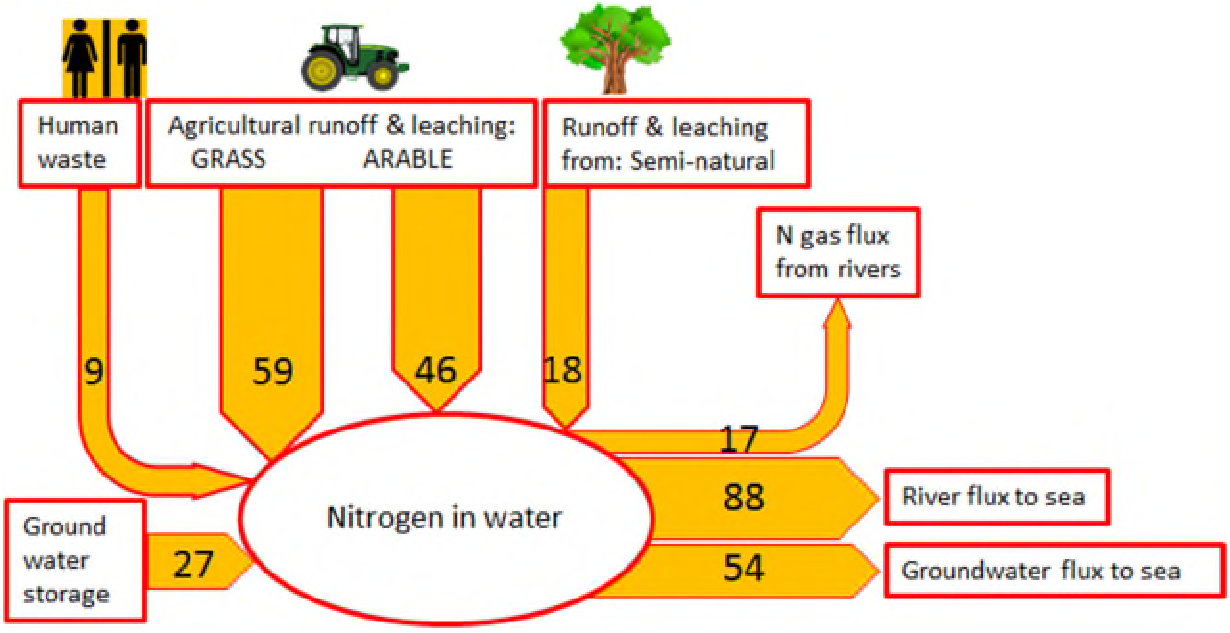


Figure 1. Hydrosphere/soil nitrogen budget (2010) using outputs from the LTLS-IM macronutrient model (kt N yr^{-1}).

3.2 Atmosphere

Atmospheric emissions

The total NH_3 emitted from all sources in Scotland is 27.8 kt NH_3-N yr^{-1}, of which 95% (25.6 kt NH_3-N yr^{-1}) is from agricultural sources. 11.1 kt NH_3-N yr^{-1} is emitted from livestock and 14.5 kt NH_3-N yr^{-1} from fertiliser and crops. The combined sectors of waste, transport and industry & household energy produce 2.3 kt NH_3-N yr^{-1}. Emissions from fertiliser application and crops also account for 91% of N_2O emissions from Scotland (18 kt N_20-N yr^{-1}).

The total NO_x emitted from all sources in Scotland is 24.4 kt NO_x-N yr^{-1}. This comes almost exclusively from transport (13.8 kt NO_x-N yr^{-1}) and industry & household energy (10.2 kt NO_x-N yr^{-1}), with a minor proportion of 0.3 kt NO_x-N yr^{-1} attributed to agricultural sources.

N gas flux from rivers is 17 kt N yr^{-1}, as derived by the LTLS-IM. All N emissions to the atmosphere quantified here add up to 89 kt N yr^{-1}.

Atmospheric deposition, export and import

The total amount of N deposited from the atmosphere in Scotland is estimated at 90.4 kt N yr^{-1} (Smith et al. 2018). Figure 2 shows that most (62 %) of the nitrogen deposition received by Scotland originates from reduced N (NH_x) sources, with 62 % these sources located in Scotland. However, N deposition from NO_x sources is largely (84 %) produced by sources outside Scotland. Of the NO_x deposition received by Scotland, 32 % is from sources in the rest of Europe, 27 % is from international shipping compared to the 16 % produced by NO_x sources in Scotland. Export flows to the outside of the UK landmass have not been quantified here, as this would require additional modelling to determine the contribution of Scotland.

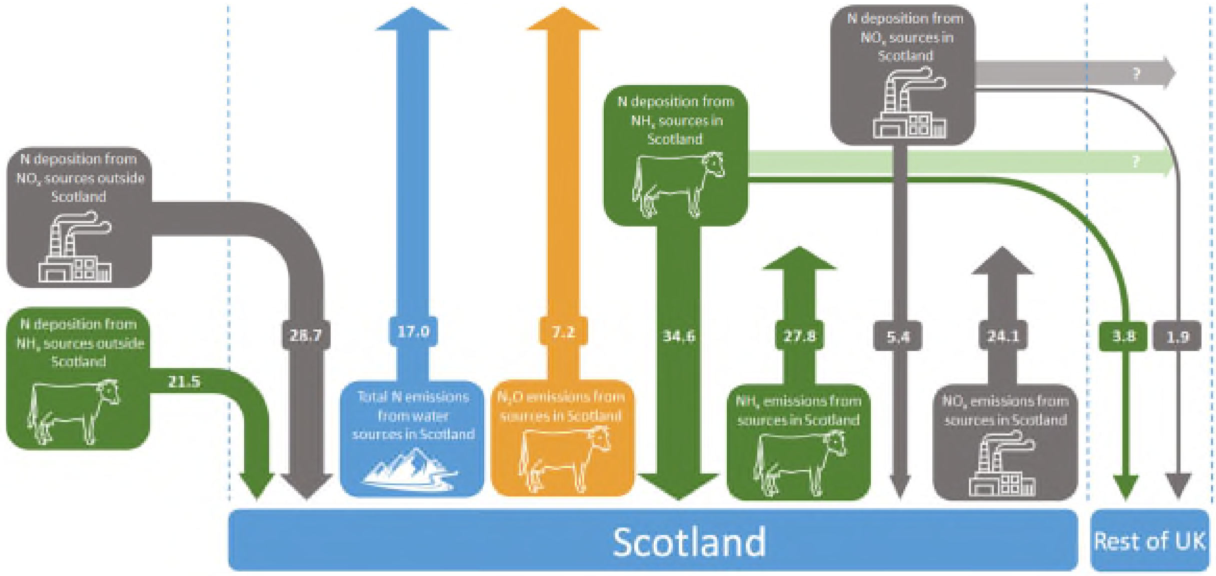


Figure 2: Atmospheric nitrogen budget for Scotland from the CBED model (kt N yr^{-1}), with atmospheric emissions from the NAEI and source apportionment and import/export derived from work by Bealey and Dore (2017) and Smith et al. (2018). Only NO_x and NH_x emissions are considered for N deposition, N_2O etc. remain in the atmosphere. N.B. values may not add up due to rounding.

Biological nitrogen fixation

Biological nitrogen fixation (BNF) is a very energy demanding process, and therefore does not take place in soils with large mineral N concentrations. Consequently, BNF is negligible in N fertilised croplands and intensively managed grasslands. Grasslands, under-sown with a high percentage of clover in organic systems or UK uplands, however can fix up to 100 kg N ha^{-1} yr^{-1}, whereas unmanaged extensively grazed grasslands N fixation by the natural flora may fix ~ 35 kg N ha^{-1} yr^{-1}. These values are rather uncertain, due to lack of specific research (Newbold, 1982). Further data collation, beyond the resources of this study, would be required to quantify BNF for Scotland (e.g. using information on organic farms).

3.3 Production, net import/export of food & feed

The N content of agricultural livestock feed, fertiliser input to soils and livestock excreta in Scotland were available from two sources, Leinonen et al. (2019), and the UK agricultural emission inventory (Table 2), for 2015. The year 2015 has been selected here for enabling direct comparison between the two datasets.

For livestock excreta, the two datasets differ by 20% overall (145 kt vs. 173 kt N), and this is due to different underlying methodologies and assumptions. Energy requirements, for example, can be calculated by the IPCC approach (2006 Guidelines) using net energy requirements (used in the agricultural inventory), or by metabolisable energy requirements (used by Leinonen et al. 2019). Furthermore, concentrate rations are estimated differently by the two data sources, with Leinonen et al. (2019) perhaps using a more detailed approach, resulting in different average N content of concentrates being used. Given the advantages and disadvantages of these two different approaches, more analysis of the underlying data is required, which is beyond the resources of this study. Therefore, the mean value of the two estimates, 159 kt N, has been used in Figure 3. N.B., in Figure 3 below, N emissions to the atmosphere from livestock housing and manure/slurry storage (12 kt N) have been subtracted from the N excreta estimated to be either applied to soils by land spreading or deposited by grazing animals (147 kt N), to avoid double-counting.

Table 2. N excretion from livestock in Scotland for 2015, based on data from the UK agricultural emission inventory (Misselbrook et al., pers. comm.) and Leinonen et al. (2019). Totals may not add up due to rounding.

		UK agricultural emission inventory (kt N)	Leinonen et al. (2019) (kt N)	Difference
Livestock excreta	Cattle	92.0	107.6	+ 17 %
Livestock excreta	Sheep	42.2	51.1	+ 21 %
Livestock excreta	Pigs	3.3	6.0	+ 82 %
Livestock excreta	Poultry	7.2	8.4	+ 17 %
Livestock excreta	**Total**	**144.7**	**173.1**	**+ 20 %**

For mineral fertiliser N inputs to soils (for arable crops and grassland), the estimate from the UK agricultural inventory (150 kt N) was used in preference to Leinonen et al. (2019; 193 kt N), as the latter includes organic materials which were already accounted for separately.

Other, more detailed, key terms that could not be quantified for the current study, due to resources, include the N content and flows of import/export of agricultural commodities (live/raw/processed) with the rest of the UK and beyond, the N flow of agricultural and other products to and within industry, crop/livestock and wood production, fisheries and aquaculture. However, partial data have been derived at SRUC, such as for milk production (7.9 kt N yr^{-1} in 2015), beef production (6.8 kt N yr^{-1} in 2015), and further ongoing work would need to be combined with agricultural statistics that are publicly available, to create a more detailed budget for agricultural production/import/export for Scotland. Further information is also already partly available from work carried out in the development of the SEPA Sector Plans and could be used as input for further work.

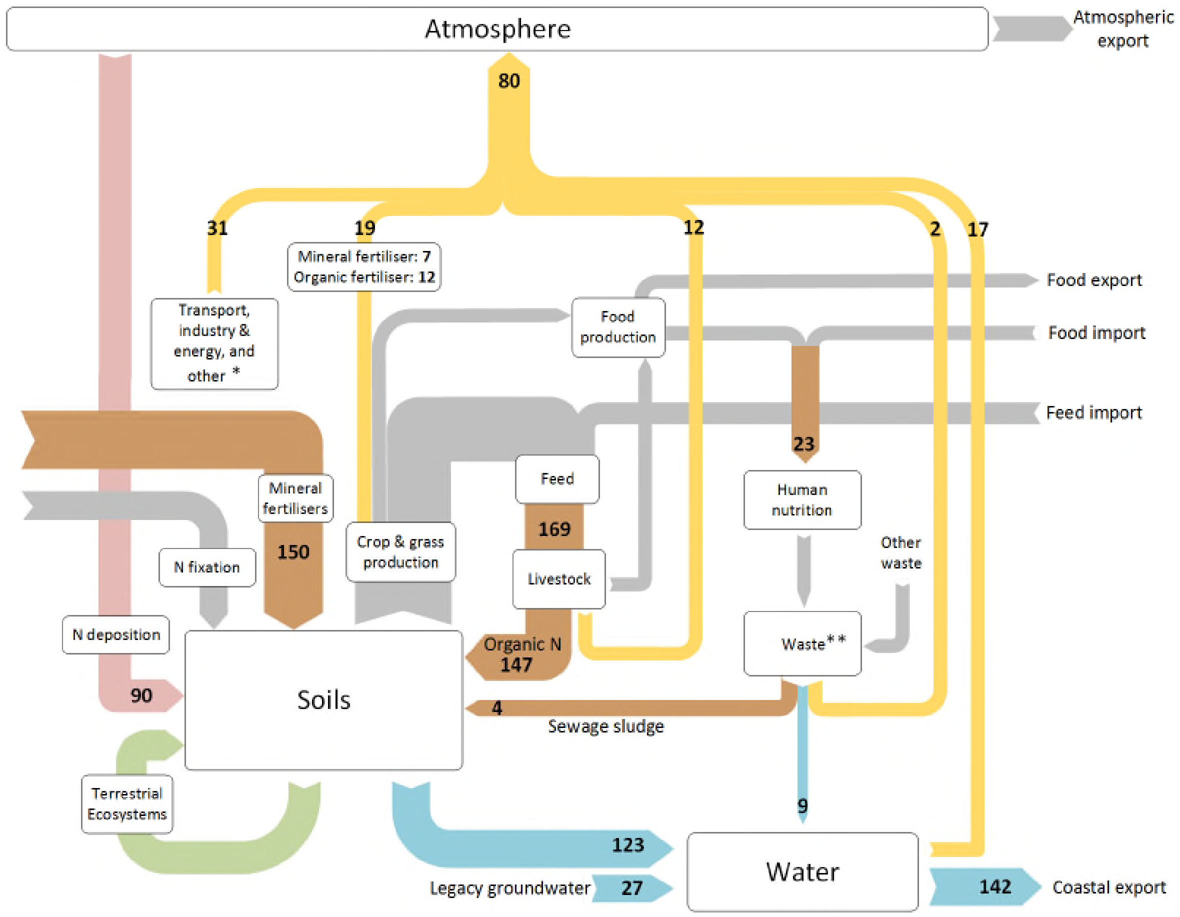
3.4 Human consumption

Human consumption of N has been estimated as 22.9 kt yr^{-1}. Other related flows which could not be quantified for this study include the N flow of food production to landfill, however, detailed data exist and are used for calculating UK emission inventory contribution (pers. comm. Sam Tomlinson – inventory improvement report to Defra in progress).

3.5 Nitrogen flows for Scotland

Once all flows are combined into a single budget diagram (Figure 3), the relative importance of the different components can be quantified: The largest "engine" of N flows in Scotland is agriculture, which converts N inputs of mineral fertilisers (150 kt N) and livestock excreta (159 kt N before atmospheric emissions from housing and storage; N.B. mean value of Leinonen et al. (2019) and UK agricultural inventory), recycled waste N (4kt) and imported feed into crop and livestock products (total feed 169 kt N). These in turn are utilised for food and feed production, including export, and to feed the Scottish population. Large amounts of N are lost from this system through various pathways, to water (132 kt N), the atmosphere (80 kt N) and waste streams. 90 kt N are deposited to Scotland by atmospheric deposition.

For some sectors (fisheries, forestry), and parts of sectors (e.g. atmospheric N pollutant export, agricultural sub-sectors, waste streams) it has not been possible to quantify N flows due to the limited resources available for the study (grey arrows in Figure 3), and further work is required (see Section 4.3). Terrestrial ecosystems (green arrow) are assumed to have a nearly closed N cycle of semi-natural systems (with the exception of N deposition input, and very small emission terms).



* "Other" includes small contributions of N emissions from off-road vehicles, fishing, and fugitive emissions mainly in the form of NO_x, and land use change mainly in the form of N_2O.

** "Waste" includes N flows from landfill, compost, sewage and anaerobic digestion. "Other waste" is shown in a very simplified way here, to avoid large numbers of arrows from food production, industry etc.

Figure 3: N flows for Scotland (kt N yr^{-1}), combining inputs and outputs between the atmosphere, hydrosphere/soil, human production/consumption and import/export (using latest available data, dates ca. 2010-2018). N.B. values may not add up due to rounding.

4. Discussion (including uncertainty & further work)

4.1 Scottish N flows

Agriculture and human consumption/production are the main driver of N flows in Scotland, which is comparable with western European countries (e.g. ENA, 2011, Leip et al. (2011)). This results in large losses of N to the environment, with substantial flows to water (132 kt N), the atmosphere (80 kt N) and N deposition to terrestrial systems (90 kt N).

4.2 Uncertainties (all sectors)

There are substantial areas of the N budget that warrant further investigation to complete the understanding of N flows between sectors, and to fill data gaps. Uncertainty and unknown/not yet quantified flows are shown in grey in Figure 3.

Overall, the quantified environmental budget components appear to be relatively robust for water (5 approaches) and atmospheric input/output. The largest uncertainty is in the unquantified flows, which require further calculations to complete the picture for Scotland. There is also some uncertainty in the agricultural flows (e.g. differences between the UK agricultural emission inventory and the work by Leinonen et al. 2019), partly arising from methodological differences and underlying assumptions, and partly from larger uncertainties in certain areas (e.g. lack of statistics on the actual amount and composition of animal feed consumed). Figure 3 gives a simplified overview of the N budget, and there are further unquantified flows, however these are expected to be relatively small (e.g. emissions of NO, N_2O and NH_3 from terrestrial ecosystems, see spreadsheet Annex A).

4.3 Further work

As a priority, the currently unknown N flows in the budget should be estimated/quantified, and the agricultural nitrogen flows at the centre of the N budget diagram un-packed and described in more detail, e.g. by sector, with import and export terms included. Data for this work should mostly be available, and further studies may already exist/be in progress. However, it was not possible to carry out a complete assessment here, due to the available resources. While further data collation and modelling is recommended, including updating of underlying data and assessments to reflect current conditions, it is not expected that any primary research/field work is required. As an example of addressing atmospheric modelling data gaps, Scotland's contribution to transboundary N deposition could be quantified with additional model runs (FRAME). Also, the latest atmospheric emission inventory estimates have just been published for the year 2017, and related data such as N input to soils (mineral and organic) are available. Other data that underlie models such as SAGIS may also need to be updated, with the agricultural data used in SAGIS, especially, now more than 5 years old (G. Cameron, SEPA, *pers. comm.*).

Improvements in the available statistical data on some agricultural activities (e.g. use of animal feed, prevalence of different manure storage and management technologies) could improve the N budget calculations. Scottish Government is currently considering enhancing the agricultural data collection for the benefit of agricultural greenhouse gas estimates (Eory *et al.* 2019), and those future data collections could provide valuable activity data for the Scottish N budget, too.

5. Conclusions

Key nitrogen flows for Scotland have been quantified in this study, bringing together the most recent available data (different years) for soils, water, air and human consumption/production (with an emphasis on agriculture, nutrition and waste). Losses of N to water (132 kt N yr^{-1}), air (80 kt N yr^{-1}) and terrestrial systems (90 kt N through atmospheric deposition) are substantial, especially to due agricultural activities and, to a smaller extent, waste recycling/processing. Improved nutrient use efficiency could increase environmental as well as economic benefits. However, further work is required to complete currently unquantified flows and provide more detail on key activities, to help develop policy options, in conjunction with SEPA's Sector Plans.

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