UK Centre for
Ecology & Hydrology

Atmospheric Modelling Data for Scottish Nitrogen Balance Sheet

Carnell E.J.

Date 22/11/2021

Contents

1 Introduction

This short report aims to update the **atmospheric nitrogen budgets** for Scotland presented in Carnell et al. (2019). The atmospheric nitrogen (N) estimates presented in the 2019 report were based on FRAME source attribution model output for the emission year 2012 (Bealey and Dore 2017), which was the most recent dataset at the time of writing. Although more up to date estimates of N deposition existed in early 2019 (when the SEPA report was written), the source attribution dataset (for the emission year 2012) was the most up to date dataset providing estimates of N deposition by source type. As a result the source attribution output was scaled to more recent CBED model estimates (for the years 2013 – 2015, Smith et al. 2018) in the Carnell et al. (2019) report, to reflect any changes in emissions and subsequent N deposition. This new report for the Scottish Government compares source attribution model outputs for the years 2012 and 2018 respectively, rather than the scaled dataset used in Carnell et al 2019.

Improved estimates of N deposition to/from Scotland now exist for the emission year 2018, which were developed under the Air Pollution Information System (APIS http://www.apis.ac.uk/) project and funded by the UK government agencies (SEPA, SNH, JNCC, EA, NE, NRW, NIEA). In addition to updated emission estimates used as model input, the model has also been updated substantially, with important developments including the differentiation of deposition from sources within the Republic of Ireland, which were previously included with European sources. More recent model input data (such as improved land cover estimates and meteorology) were also used in this work which better reflect the present.

2 Methodology

2.1 Source attribution model description

Nitrogen deposition estimates for the year 2018 were modelled using the FRAME (Fine Resolution Multi-pollutant Exchange) model. FRAME is a Lagrangian atmospheric transport model used to assess the annual mean deposition of reduced (NH_x) and oxidised (NO_y) nitrogen and sulfur over the United Kingdom. The domain of the model covers the British Isles with a grid resolution of 5km.

Emissions of ammonia (NH_3), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) were separated into 163 different sub-sectoral emission categories. This included three additional categories to the 160 UK/European sources used in the previous iteration (see Bealey & Dore 2017 for details), to allow for the separation of emission sources from the Republic of Ireland (which were previously included with European emissions).

Aside from the separation of emissions from the Republic of Ireland, the model footprint definitions remain consistent with the previous source attribution model run (for the year 2012). This included 22 individual point sources and background 'area source' emissions of SO_2, NO_x and NH_3 split into 11 SNAP sectors (Selected Nomenclature for Air Pollution, European Environment Agency, 2013), international shipping and European emissions. The 11 SNAP sectors are - energy production and transformation; commercial institutional and residential combustion; industrial combustion; industrial processes; solvent use; road transport; other transport; waste treatment and disposal; agriculture; and natural. The top 22 point sources were isolated as they are of interest to regulators. They were made up of power stations (12), refineries (5), steel works (3), auto generators (1), and other industrial combustion (1).

2.2 Emission estimates used

Ammonia, nitrogen dioxide and sulfur emissions for the year 2018 were downloaded from the UK National Atmospheric Emissions Inventory (NAEI http://naei.beis.gov.uk) and used as input into the model. NH_3 input emissions were split into 5 sectors, rather than the full set of SNAP sectors as for NOx and SO_2 – agriculture split into livestock and mineral fertiliser; non-agricultural abatable sources (e.g. remaining point sources, transport, solvents, industry, power generation); non-agricultural non-abatable sources (wild birds and animals, pets, non-agricultural horses, all human-related emissions); and non-agricultural sources from the waste sector (including anaerobic digesters).

Regional land masks were applied to the emission maps to separate sources by country i.e. England, Scotland, Wales, Northern Ireland and Republic of Ireland.

3 Results

3.1 NH_3 emission totals

The total NH_3 emitted from all sources in Scotland in 2018 was 26.1 kt NH_3-N yr^{-1}, of which ~84% (21.7 kt NH_3-N yr^{-1}, Table 1) was produced by agricultural sources. 18.2 kt NH_3-N yr^{-1} was emitted from activities associated with livestock (including spreading of manures and FYM) and 3.5 kt NH_3-N yr^{-1} from the application of synthetic fertiliser. The combined sectors of waste, transport and industry, households & energy produce 4.2 kt NH_3-N yr^{-1}. Total NH_3 emissions in Scotland are 4.8 kt NH_3-N lower than those used in the last source attribution run (for the emission year 2012). The 2018 emission dataset estimated decreased emissions from cattle and the waste sector. However, this is primarily due to methodological changes in the estimation of these sources, with back cast emissions for the year 2012 estimated to be 0.17 kt NH_3-N lower than for 2018. Overall UK NH_3 emissions in the 2018 run are 10.5 kt NH_3-N lower than the 2012 run, with emissions estimated to decrease from 233.2 kt NH_3-N (in 2012) to 222.6 kt NH_3-N (in 2018).

***Table 1**: A comparison between 2012 and 2018 estimates of NH_3-N emissions from Scottish sources (as used in the FRAME source attribution model).*

Emission Source	2012 (kt N yr^{-1})	2018 (kt N yr^{-1})	% Difference	Difference (kt N yr^{-1})
Cattle	15.7	13.5	-14.0%	-2.2
Sheep	1.6	1.6	0.0%	0.0
Pigs	1.1	0.9	-18.2%	-0.2
Poultry	1.9	2.1	10.5%	0.2
Minor livestock (horses, goats, farmed deer)	0.4	0.1	-75.0%	-0.3
Mineral fertilisers	3.8	3.5	-7.9%	-0.3
Non-Agricultural (abatable)	0.8	0.6	-25.0%	-0.2
Non-Agricultural (non-abatable)	3.4	3.1	-8.8%	-0.3
Non-Agricultural waste	2.0	0.6	-70.4%	-1.4
Point sources	0.2	0.1	-50.0%	-0.1
Total	**30.9**	**26.1**	**-15.5%**	**-4.8**

3.2 NO_x emission totals

The total NO_x emitted from all sources in Scotland was 21.5 kt NO_x-N yr^{-1}. This predominantly originated from transport (11.1 kt NO_x-N yr^{-1}, Table 2), point source emissions (5.4 kt NO_x-N yr^{-1}) industry and other stationary combustion (3.5 kt NO_x-N yr^{-1}), with a smaller contribution of 1.3 kt NO_x-N yr^{-1} attributed to agricultural sources. Overall NO_x emissions from Scotland were 6.07 kt NO_x-N lower than those used in the previous source attribution model run (for 2012). Emissions from the road transport sector were 1.6 kt NO_x-N lower than those used for the 2012 run, which has been partially offset by the inclusion of agricultural NO_x-N emissions to the emission inventory.

Taking into consideration of methodological changes, the latest back cast emission estimates for Scotland suggest that NO_x emissions have decreased by 9.9 kt NO_x-N (NAEI http://naei.beis.gov.uk) between the two source attribution model runs, which is primarily attributed to reductions in emissions from power stations (primarily point source emissions). Back cast NO_x emission estimates for the UK are estimated to have decreased by 181.7 kt NO_x-N emissions, which again is primarily due to reductions in emissions associated with power stations.

***Table 2**: A comparison between 2012 and 2018 estimates of diffuse and point source NO_x-N emissions from Scottish sources (as used in the FRAME source attribution model).*

SNAP	Description	2012 (kt N yr-1)	2018 (kt N yr-1)	% Difference	Difference (kt N yr-1)
S1	Publicpower	0.1	0.0	-73%	-0.08
S2	Other Stationary Combustion	1.9	1.5	-18%	-0.33
S3	Industry	1.4	1.9	38%	0.52
S4	Production	0.0	0.0	NA	0.00
S5	Fugitive	0.0	0.0	NA	0.00
S6	Solvents	0.0	0.0	NA	0.00
S7	Road Transport	8.3	6.7	-19%	-1.60
S8	Other Transport	5.0	4.4	-13%	-0.67
S9	Waste	0.0	0.0	0%	0.00
S10	Agriculture	0.0	1.3	NA	1.31
S11	Other	0.1	0.2	125%	0.10
	Point sources	10.7	5.4	-50%	-5.33
Total		27.6	21.5	-22%	-6.07

3.3 Sulfur emissions

UK sulfur emissions used in the model are estimated to have decreased from 180.6 kt SO_2-S (2012) to 77.8 kt SO_2-S (2018) between the two model runs. Sulfur emissions are an important input to atmospheric chemical transport models (such as FRAME) as the availability of sulfur in the atmosphere affects the chemical transformations and lifetime of ammonia gas. Ammonium sulfate, a reaction product of ammonia and SO_2 is deposited as wet NH_x deposition and so decreased sulfur emissions are expected result in lower N deposition and NH_3 gas remaining in the atmosphere for longer. Backcast emission estimates (from the NAEI http://naei.beis.gov.uk) suggest UK sulfur emissions decreased by 73 % between 2012 and 2018.

3.4 Total atmospheric N deposition received by Scotland

The total amount of N deposited from the atmosphere in Scotland is estimated at 67.4 kt N yr^{-1} (FRAME model output for the emission year 2018). Table 3 shows that 35 % of the nitrogen deposition received by Scotland originates from sources within Scotland, with a similar proportion coming from European sources. The rest of the UK (England, Wales, Northern Ireland) contributes 23 % and international shipping ~8%.

Overall N deposition to Scotland is estimated to have decreased by 10.2 kt N yr^{-1} compared with the 2012 dataset. This reduction is largely attributed to lower N deposition from sources in Scotland (and the rest of the UK), which has been partially offset by increased deposition from European (inc Republic of Ireland). This increase in European deposition is likely due to methodological changes to the Republic of Ireland (RoI) emissions used as input to the model.

Since the last source attribution run (for the emission year 2012) emission estimates for the RoI have been improved significantly both in terms of completeness and spatial resolution. In particular NO_x emissions from the RoI have increased with improved emission data, between the two model runs, from 26.8 kt NO_2 to 117 kt NO_2. Ammonia emissions also increased (to a lesser extent), from 103.6 kt NH_3 to 119.4 kt NH_3 and SO_2 from 6.1 kt SO_2 to 12.5 kt SO_2. The increased N deposition from European sources is therefore likely to be a result of methodological changes rather than real increases in emissions.

Table 3: *A comparison between 2012 and 2018 Total N deposition received by Scotland (FRAME source attribution model output). The table excludes offshore emissions as deposition to Scotland from these sources was < 0.001 kt N.*

Source of N deposition	2012		2018		% difference	Absolute difference (kt N yr^{-1})
	kt N yr^{-1}	% of total	kt N yr^{-1}	% of total		
England	13.5	17%	10.2	15%	-24.2	-3.3
Wales	1.1	1%	0.7	1%	-33.3	-0.4
Scotland	33.6	43%	23.5	35%	-30.1	-10.1
Northern Ireland	5.0	6%	4.4	6%	-12.6	-0.6
Europe*	16.7	21%	23.5	35%	40.4	6.8
International Shipping	8.3	11%	5.7	8%	-30.9	-2.6
Total	**78.11**		**67.94**		**-13%**	**-10.2**

**Includes the Republic of Ireland to allow for comparison with 2012 (where sources from Europe and Republic of Ireland were combined)*

3.5 Composition of atmospheric N deposition received by Scotland

The composition of N deposition received by Scotland is presented in Figure 1, it clearly shows that the majority of deposition received is in the form of NH_x deposition i.e. derived from NH_3 emissions. A high proportion of the deposition received is also in the form of wet deposition from regional and international sources. Wet NH_x deposition to Scotland from Scottish emission sources appears to have decreased between 2012 and 2018, this is likely to be a result of decreased agricultural NH_3 emissions in Scotland (see Table 1).

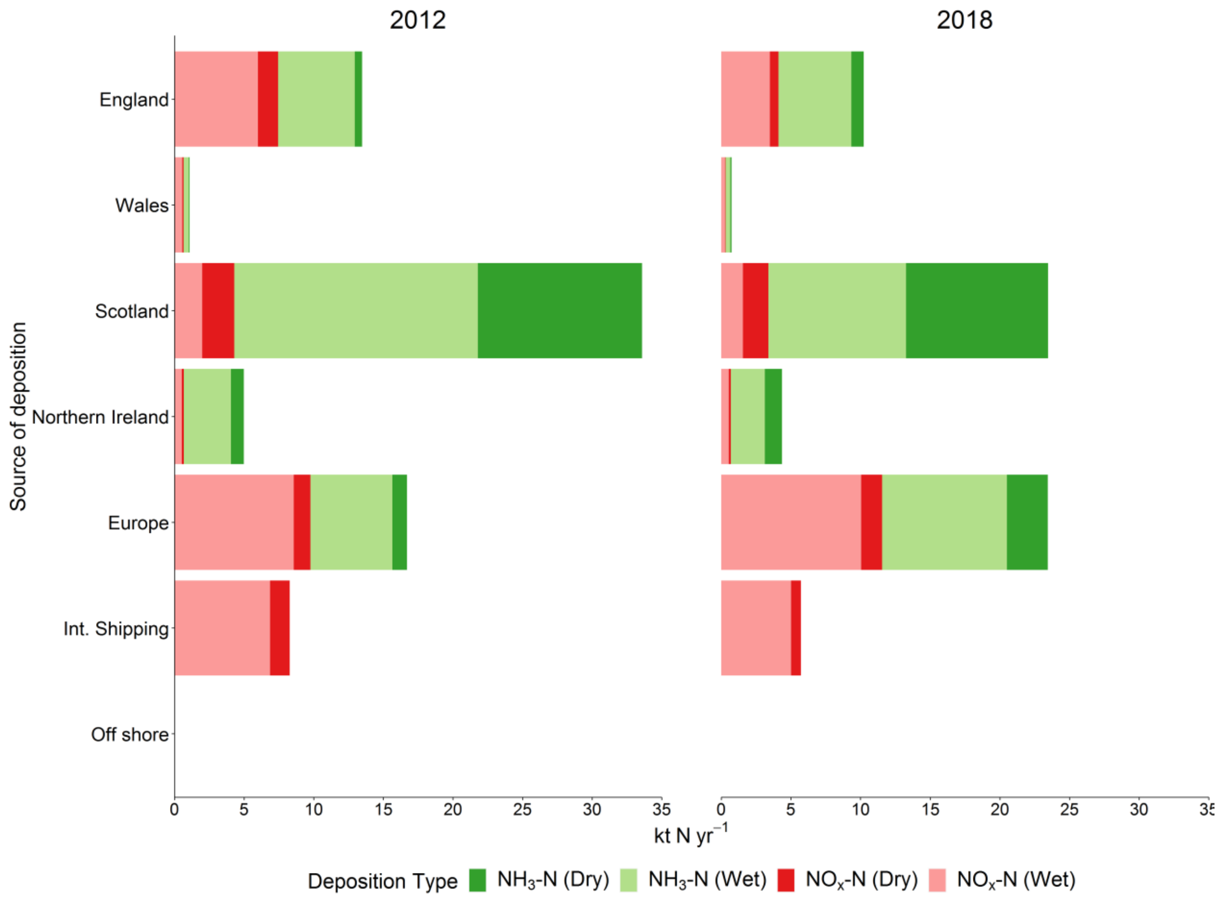

***Figure 1**: A comparison between 2012 and 2018 N deposition received by Scotland separated by form of N deposition (FRAME source attribution model output).*

3.6 Source of atmospheric N deposition received by Scotland

Sources of N deposition received by Scotland are presented in Table 4 and Figure 2. The table shows that over half of the N deposition produced by and depositing within Scotland comes from emissions associated with livestock farming. Non-agricultural non-abatable sources in Scotland are also a significant contribution to N deposition received by Scotland (~3.5 kt N), this is likely to predominantly originate from seabirds. Sources within the Republic of Ireland produce 6.1 kt N yr^{-1} of N deposition received by Scotland, this equates to ~26 % of the combined European deposition (inc. Republic of Ireland) presented in Table 3. The proportional contribution of emission source categories to total N deposition received by Scotland is presented in Figure 2. The figure clearly shows an overall decline in N deposition from Scottish livestock, which has been offset by increased European sources (see Section 3.3).

Table 4: *Total N deposition received by Scotland, based on FRAME source attribution model output for the year 2018. The table excludes offshore emissions as deposition to Scotland from these sources was < 0.001 kt N.*

Source of Deposition	Scotland	England	Wales	N. Ireland	R.O. Ireland	Europe	Int. Shipping	Total
Livestock	13.1	4.3	0.4	3.2	-	-	-	20.9
Agriculture (other)	2.9	1.3	0.1	0.3	-	-	-	4.5
Transport	2.4	2.4	0.2	0.3	-	-	-	5.3
Non-agricultural (abateable)	0.9	0.3	0.0	0.2	-	-	-	1.4
Non-agricultural (non-abateable)	3.5	0.4	0.0	0.1	-	-	-	4.0
Other Sources	0.6	1.0	0.1	0.3	-	-	-	2.0
Point Sources	0.1	0.6	0.1	0.0	-	-	-	0.8
Rep. of Ireland NH_3 sources	-	-	-	-	4.3	-	-	4.3
Rep. of Ireland NO_x sources	-	-	-	-	1.8	-	-	1.8
European sources	-	-	-	-	-	17.3	-	17.3
Int. Shipping	-	-	-	-	-	-	5.7	5.7
Total	**23.5**	**10.2**	**0.7**	**4.4**	**6.1**	**17.3**	**5.7**	**67.9**

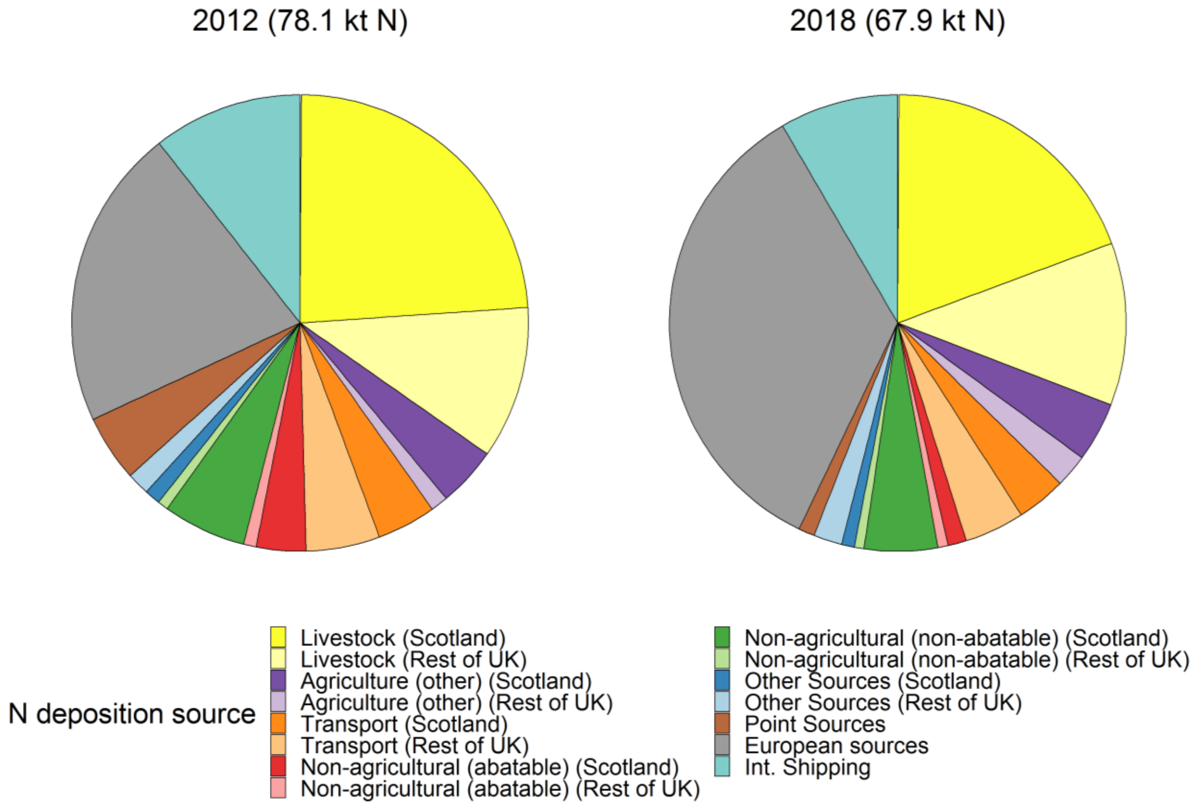

Figure 2*: Proportional contribution of emission source categories to total N deposition received by Scotland. A comparison between FRAME model output for the years 2012 and 2018.*

3.7 N deposition originating from Scotland

Table 5 presents the amount of N deposition received by the UK from emission sources located within Scotland. The table clearly shows that the majority of N deposition originating from Scotland is deposited within Scotland. This is unsurprising given the south westerly prevailing wind conditions in the UK. It is unfortunately not possible (with the current model set up) to estimate the proportion of Scottish emissions that are exported outside of the UK domain.

Table 5*: 2018 N deposition produced by emission sources located in Scotland separated by UK country receiving deposition (kt N yr^{-1})*

Source of N Deposition	Location of N deposition				
	Scotland	England	Wales	Northern Ireland	Total
Livestock	13.1	1.2	0.1	0.2	14.6
Agriculture (other)	2.9	0.2	0.0	0.0	3.1
Transport	2.4	0.6	0.1	0.1	3.1
Non-agricultural (abatable)	0.9	0.1	0.0	0.0	1.0
Non-agricultural (non-abatable)	3.5	0.1	0.0	0.0	3.7
Other Sources	0.6	0.2	0.0	0.0	0.9
Point Sources	0.1	0.0	0.0	0.0	0.2
Total	**23.5**	**2.4**	**0.2**	**0.4**	**26.5**

3.8 Atmospheric NH_x and NO_x Budget for Scotland

The following section provides an update to the Atmospheric N budget diagram presented in Carnell et al. (2019). All N flows in Figure 3 are based on FRAME source attribution model input/output for the emission years 2012 and 2018 respectively. Some N inputs to the atmosphere are not shown in Figure 3 as they do not deposit easily and are therefore not used by the FRAME model. These include N_2O emissions (which typically remain in the atmosphere as long-lived greenhouse gases) and emissions of N_2 from hydrological sources (please see Bell et al. 2021 for details).

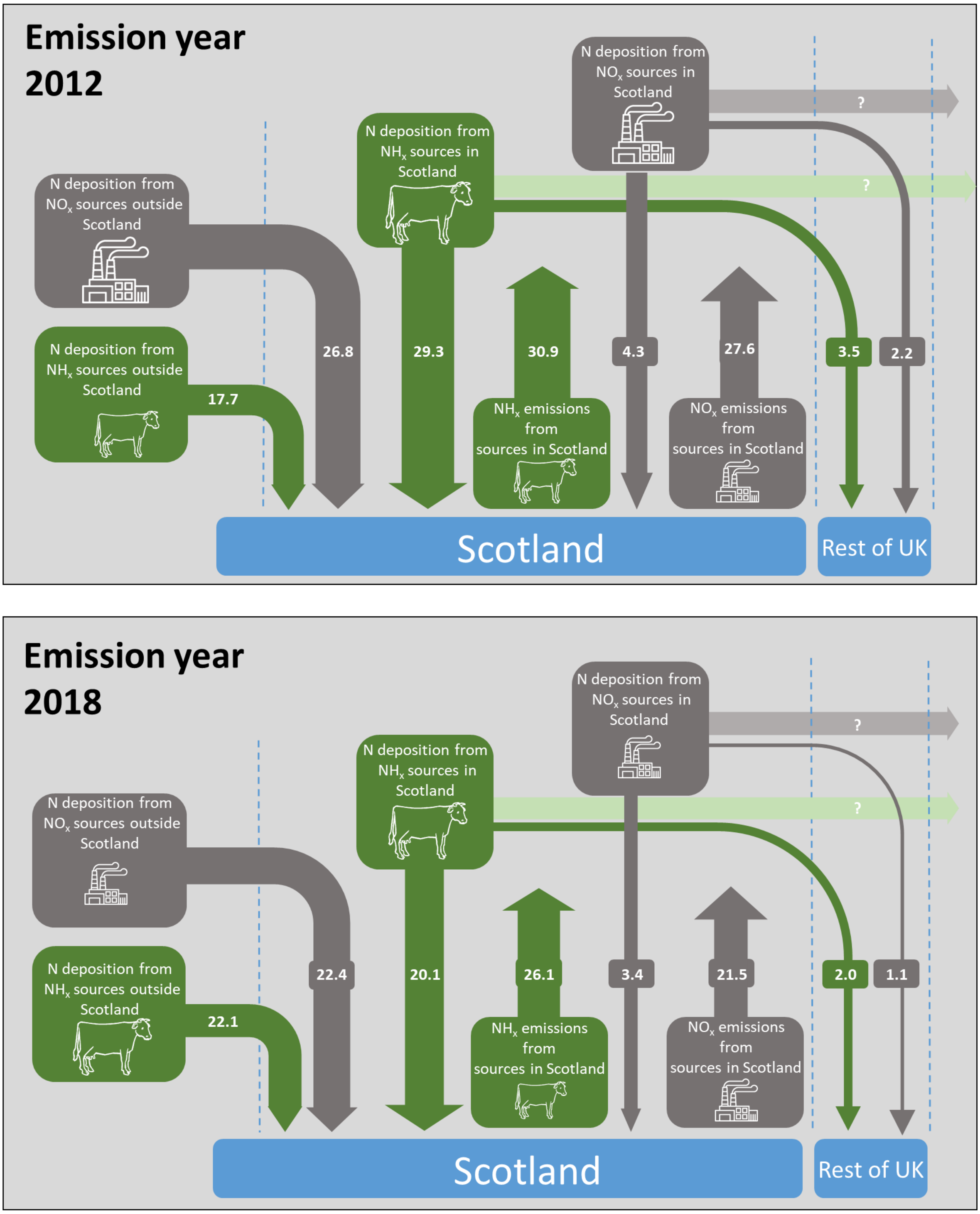

Figure 3: Atmospheric NH_x and NO_x budget for Scotland based on FRAME source attribution model input/output (kt N yr^{-1}) for the emission years 2012 and 2018

Summary and Discussion

The latest FRAME source attribution model output for the year 2018 provides more up to date deposition estimates for Scotland than were reported previously in Carnell et al. (2019). This latest model run includes more recent emission estimates (for the year 2018) as well as a number of improvements to the model. In particular NO_x emissions from the Republic of Ireland (RoI) are now much more complete and are considered to be a better reflection of emission activities in the RoI (NO_x emission estimates from the RoI increased from 26.8 kt NO_2 to 117 kt NO_2 between the two model runs).

Taking into consideration methodological differences between the two years, Scottish NH_3 emissions are estimated to have remained relativity stable between the two model runs (0.17 kt NH_3-N reduction from 2012 to 2018), while Scottish NO_x emissions are estimated to have decreased by 9.9 kt NO_x-N (a significant reduction compared to the 6.1 kt NO_x-N reduction modelled), mainly due to major power stations being decommissioned.

Approximately 65% of the N deposition to Scotland is from emission sources outside of Scotland. Approximately 35 % of the total N deposition to Scotland originates from Scottish sources, 25.5 % is from European (exc. RoI) sources, 22 % from the rest of the UK (i.e. England, Wales and Northern Ireland), 9 % from Republic of Ireland and 8.5 % from international shipping.

Most of the N deposition to Scotland originating from Scottish sources is in the form of NH_x (~85%). The majority of this deposition from Scottish NH_x sources is from livestock farming, which contributes ~20 % of the total N deposition received by Scotland.

Most of the emissions generated within Scotland are deposited within Scotland, with only 11 % being deposited to the rest of the UK. Unfortunately due to the way the FRAME model has been set up, it is not possible to quantify what proportion of emissions from Scottish sources is transported outside the UK to the Republic of Ireland and Europe.

4 Reference

Bealey, W.J.; Dore, A.J. (2017). Source Attribution - deposition of nitrogen and sulphur to UK. NERC Environmental Information Data Centre. https://doi.org/10.5285/e5bfac9b-0642-4b5b-a780-e5801b2dab8bCarnell E.J., Thomas I.N., Tomlinson S.J., Bell V.A., May L., Skiba U., Dore A.J., Eory V., Dragosits U. (2019) A Nitrogen Budget for Scotland. Report to SEPA

Bell V.A., Lane R.A., Davies, H.N. (2021) Regional Freshwater Nitrogen Budgets for Scotland. Report to Scottish Government, August 2021

Misselbrook T.H., Gilhespy S.L., Cardenas L.M., Williams J. and Dragosits U. (2016) Inventory of Ammonia Emissions from UK Agriculture 2015. Defra Contract Report (SCF0102). Rothamsted Research, North Wyke, Devon. 36 pp.

Smith, R.I., Dore, A.J., Tang, Y.S., Stedman, J.R. (2018). Sulphur and nitrogen atmospheric Concentration Based Estimated Deposition (CBED) data for the UK (2013-2015). NERC Environmental Information Data Centre. https://doi.org/10.5285/fd8151e9-0ee2-4dfa-a254-470c9bb9bc1e

BANGOR
UK Centre for Ecology & Hydrology
Environment Centre Wales
Deiniol Road
Bangor
Gwynedd
LL57 2UW
United Kingdom
T: +44 (0)1248 374500
F: +44 (0)1248 362133

EDINBURGH
UK Centre for Ecology & Hydrology
Bush Estate
Penicuik
Midlothian
EH26 0QB
United Kingdom
T: +44 (0)131 4454343
F: +44 (0)131 4453943

LANCASTER
UK Centre for Ecology & Hydrology
Lancaster Environment Centre
Library Avenue
Bailrigg
Lancaster
LA1 4AP
United Kingdom
T: +44 (0)1524 595800
F: +44 (0)1524 61536

WALLINGFORD (Headquarters)
UK Centre for Ecology & Hydrology
Maclean Building
Benson Lane
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB
United Kingdom
T: +44 (0)1491 838800
F: +44 (0)1491 692424

enquiries@ceh.ac.uk

www.ceh.ac.uk