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Swedish National Nitrogen Budget - Forest and semi-natural vegetation

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This report has been reviewed and approved in accordance with IVL's audited and approved management system.

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Summary

In this report, pool 4 "Forest and semi-natural vegetation" (FS) of the Swedish National Nitrogen Budget (NNB) is presented. The FS pool is divided into the three compartments; Forest (FO), Wetland (WL) and Other land (OL, which consists mostly of mountains). The FS pool is of relatively high importance for the Swedish NNB since the three land use categories (FO, WL, OL) together amount to 71% of the country area.

The inflows of reactive nitrogen (Nr) are atmospheric deposition, nitrogen fixation, and forest fertilization. The outflows are nitrogen leaching, denitrification and harvest of biomass. The Swedish data presented in this report are for year 2015 whenever possible. If data was not available for 2015, available data for the closest year to 2015 was chosen. The data was collected from Swedish official statistics and reports and preferably from sources that will continue to be updated to facilitate the evaluation of possible changes in N-budgets in the future.

In total, the FS pool has inflows of 175.8 kilotonnes (kt) N and outflows of 188.6 kt N. The largest inflow to the pool is from atmospheric deposition (99.3 kt N) and the largest outflow from the pool is via leaching/runoff (67.4 kt N). Forestry is a major industry in Sweden and the flow of N from FS.FO due to harvest is the second largest outflow from the entire FS-pool (58.5 kt N). Biological fixation of N has shown to be an important inflow for FS.FO (39.5 kt N) and comparatively even more so for FS.WL (32.1 kt N). FS.OL is of smaller quantitative importance for the flows of the FS-pool and only has two flows: leaching/runoff and deposition (2.9 kt N and 2.9 kt N, respectively).

There are several sources of uncertainties in the calculations, perhaps the most evident are uncertainties associated with denitrification rates and N-fixation rates as these processes vary across time and space and are difficult to estimate on a national level. Another large uncertainty lies in the choice of the biomass N-content used in the calculations of N-outflow due to harvesting. While the available information about the amount of biomass removed from the forest is most likely robust, the estimates of N-content of different parts of the trees vary rather widely. The highest values could almost triple the outflow of N relative to the values chosen in this report. Another question is the discrepancy between the reported build-up of C stock in the FS pool and the availability of N to make that possible. During this work with constructing a budget for the "Forest and semi-natural vegetation" pool for the Swedish NNB it has become clear that there are several issues that will have to be further investigated and improved in the future.

Sammanfattning

I denna rapport presenteras pool 4 ”Skogs- och semi-naturlig vegetation” (FS) i den svenska nationella kvävebudgeten (NNB). FS-poolen är indelad i tre kategorier; skog (FO), våtmark (WL) och övrigt land (OL, bestående mestadels av fjäll). FS-poolen är av relativt stor betydelse för den svenska NNB eftersom de tre markanvändningskategorierna (FO, WL, OL) tillsammans uppgår till 71% av landområdet.

Inflöden av reaktivt kväve (Nr) är atmosfärisk deposition, kvävefixering och skogsgödsling. Utflöden är kväveutlakning, denitrifikation och skörd av biomassa. De svenska data som presenteras i denna rapport är för år 2015 när så är möjligt. Om data inte fanns tillgängliga för 2015 valdes tillgänglig information för året närmast 2015. Uppgifterna samlades in från svensk officiell statistik och rapporter och företrädesvis från källor som kommer att fortsätta uppdateras, detta för att göra det lättare att utvärdera möjliga förändringar i N-budgetar i framtiden.

Totalt har FS-poolen inflöden på 175.8 kiloton (kt) N och utflöden på 188.6 kt N. Det största inflödet till poolen är från atmosfärisk deposition (99.3 kt N) och det största utflödet från poolen är via utlakning / avrinning (67.4 kt N). Skogsbruk är en stor industri i Sverige, och flödet av N från FS.FO på grund av uttag av biomassa från skog är det näst största utflödet från hela FS-poolen (58.5 kt N). Biologisk fixering av N har visat sig vara ett viktigt inflöde för FS.FO (39.5 kt N) och jämförelsevis ännu mer för FS.WL (32.1 kt N). FS.OL är av mindre kvantitativ betydelse för flödena i FS-poolen och har bara två flöden: utlakning / avrinning och atmosfärisk deposition (2.9 kt N och 2.9 kt N).

Det finns flera källor till osäkerheter i beräkningarna, kanske de mest uppenbara är osäkerheterna förknippade med denitrifikation och N-fixering då dessa processer varierar i tid och rum och är svåra att uppskatta på nationell nivå. En annan stor osäkerhet ligger i valet av N-halt i biomassa som används i beräkningarna av N-utflöde på grund av biomassauttag från skog. Medan den tillgängliga informationen om biomassauttag troligen är robust, varierar beräkningarna av N-halten ganska mycket. De högsta värdena kan nästan tredubbla utflödet av N relativt de värden som valts i denna rapport. En annan fråga är avvikelsen mellan den rapporterade uppbyggnaden av C-lager i FS-poolen och tillgängligheten av N för att göra det möjligt. Under detta arbete med att upprätta en budget för FS-poolen för den svenska NNB har det tydligt framgått att det finns flera frågeställningar som måste utredas och utvecklas i framtiden.

Introduction

The Task Force on Reactive Nitrogen (TFRN) was established under the Working Group on Strategies and Review (WGSR) by the Executive Body at its twenty-fifth session in December 2007.

The purpose of TFRN has been defined as: *"The Task Force will develop in the long-term technical and scientific information and options which can be used for strategy development across the UNECE to encourage coordination of air pollution policies on nitrogen in the context of the nitrogen cycle and which may be used by other bodies outside the Convention in consideration of other control measures."* For the full terms of reference of the Task Force, see Executive Body decision 2007/1 https://www.unece.org/env/lrtap/executivebody/eb_decision.html.

At the first meeting (Wageningen, 2008) TFRN agreed to define reactive nitrogen (Nr) as all biologically active, photochemically reactive and radiatively active N compounds in the biosphere and atmosphere. This meant, in practice, all N except N_2 gas; for example, nitric oxide, nitrogen dioxide, nitrate (NO_3^-), organic N compounds, nitrous oxide (N_2O), ammonia (NH_3) and ammonium (NH_4^+). At the same meeting it was proposed that an expert panel could help in preparing for the reporting of national budgets, first exploring methodologies and providing a reference template for the compilation. The Expert Panel on Nitrogen Budgets (EPNB) was established (first as an ad-hoc group) and commenced work to prepare guidelines for compilations of national N budgets of individual countries. EPNB prepared the "Guidance Document on National Nitrogen Budgets". The document was presented and approved at the 31st meeting of the Executive Body of the Convention on Long-Range Transboundary Air Pollution in December 2012. The document can be downloaded from http://www.clrtap-tfrn.org/sites/clrtap-tfrn.org/files/documents/EPNB_new/ECE_EB.AIR_119_ENG.pdf. After that, the work of EPNB continued to provide detailed guidelines for each of the eight main parts of the National Nitrogen Budget (NNB) summarised in Annexes to the ECE/EB.AIR/119 – "Guidance document on national nitrogen budgets". Currently the version dated 21. 09. 2016 is available at http://www.clrtap-tfrn.org/sites/clrtap-tfrn.org/files/documents/EPNB_new/EPNB_annex_20160921_public.pdf and it summarises six out of the eight pools. As of September 17, 2019, also the "Energy" Annex has been made available (http://www.clrtap-tfrn.org/sites/clrtap-tfrn.org/files/documents/EPNB_new/EPNB_annex_1_EF_190913.pdf). Annex 5 Waste is still under development.

NNB have been constructed for Switzerland (Heldstab et al., 2010 and 2013), Germany (Geupel et al., 2009), Denmark (Hutchings et al., 2014) and for Canada (Clair et al., 2014). These national budget calculations have not followed the EPBN methodology as it was not available at the time but provide information on the most important flows. Bach et al. (UBA, 2020) used the TFRN Guidance document and compiled a NNB for Germany which includes all eight pools described in the document. In Europe, Sutton et al. (2011) estimated that 74% of the total input of reactive nitrogen to the environment stems from the Haber-Bosch process, 16% from combustion, and the remaining 10% from biological fixation, import of feed and products. Leip et al. (2011) calculated nitrogen fluxes for EU27 developing and using the same protocol for all countries. The study by Leip et al. (2011) also recommend development of national nitrogen budgets since the assessment and management of the budgets could become an effective tool to prioritise measures and prevent unwanted effects.

NNB following the TFRN methodology are constructed based on eight pools (Figure 1). In this report, pool 4 "Forest and semi-natural vegetation" is presented. Detailed guidelines on constructing the "Forest and semi-natural vegetation" (FS) pool can be found in Annex 4 of the ECE/EB.AIR/119 "Guidance document on national nitrogen budgets" and will hereafter in this report be referred to as Annex 4. As described in Annex 4, the FS-pool is divided into: Forest (FO), Wetland (WL) and Other land (OL), of which each part consists of soil and vegetation. The FS pool is of relatively high importance for Sweden since a large area of the country is covered by forests, wetlands and mountains.

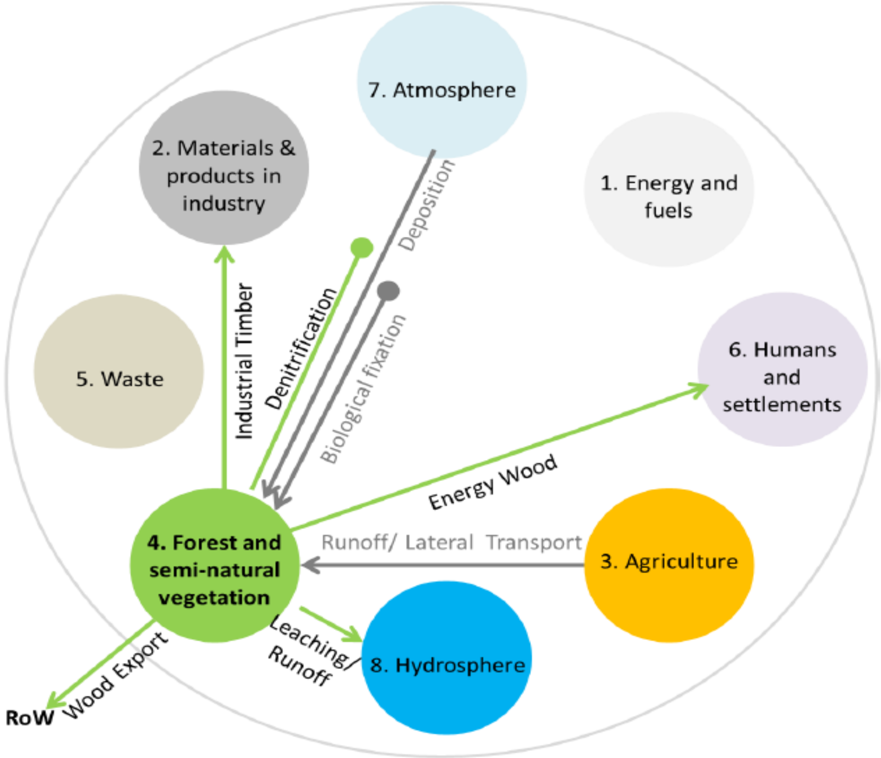

Figure 1. Nitrogen flows between the "Forest and semi-natural vegetation" pool and the other pools of the National Nitrogen Budget (including the pool "Rest of the world", RoW). Grey arrows represent nitrogen flows entering the "Forest and semi-natural vegetation" pool from the other pools; green arrows show nitrogen flows from the FS pool to the other pools. (Source: http://www.clrtap-tfrn.org/sites/clrtap-tfrn.org/files/documents/EPNB_new/EPNB_annex_20160921_public.pdf)

National nitrogen budget (NNB) for Forest and semi-natural vegetation (pool 4)

Identification of flows and data sources

The FS pool consists of three sub-pools defined according to three land-use categories: Wetlands (WL), Forests (FO) and other semi-natural vegetation termed Other land (OL), (Figure 2). OL is in

Swedish conditions dominated by mountainous areas above the tree level, the Swedish "fjäll". "Other land" does not include agricultural land or urban areas. The flows of Nr to and from FS are linked to other NNB major pools (Figure 2), with the largest Nr inflow through atmospheric deposition and the largest export through leaching of Nr (including organic N) to the hydrosphere; for forest land there is also a large export of Nr through harvesting. In this study, there are no connections to three of the NNB pools; Agriculture, Energy & fuels and Waste. Arguably the Nr flow associated with use of woody biomass for energy production could be linked to the pool Energy and fuels, but according to TFRN methodology this material flow is defined as a flow between FS and the pool Humans and settlements, sub-pool Material World. TFRN methodology considers Nr flow from Agriculture to FS in the form of Nr leaching from Agriculture which reaches wetlands. In Sweden this flow was included as leaching to Hydrosphere (Stadmark et al., 2020) and was not linked to FS to avoid double-counting.

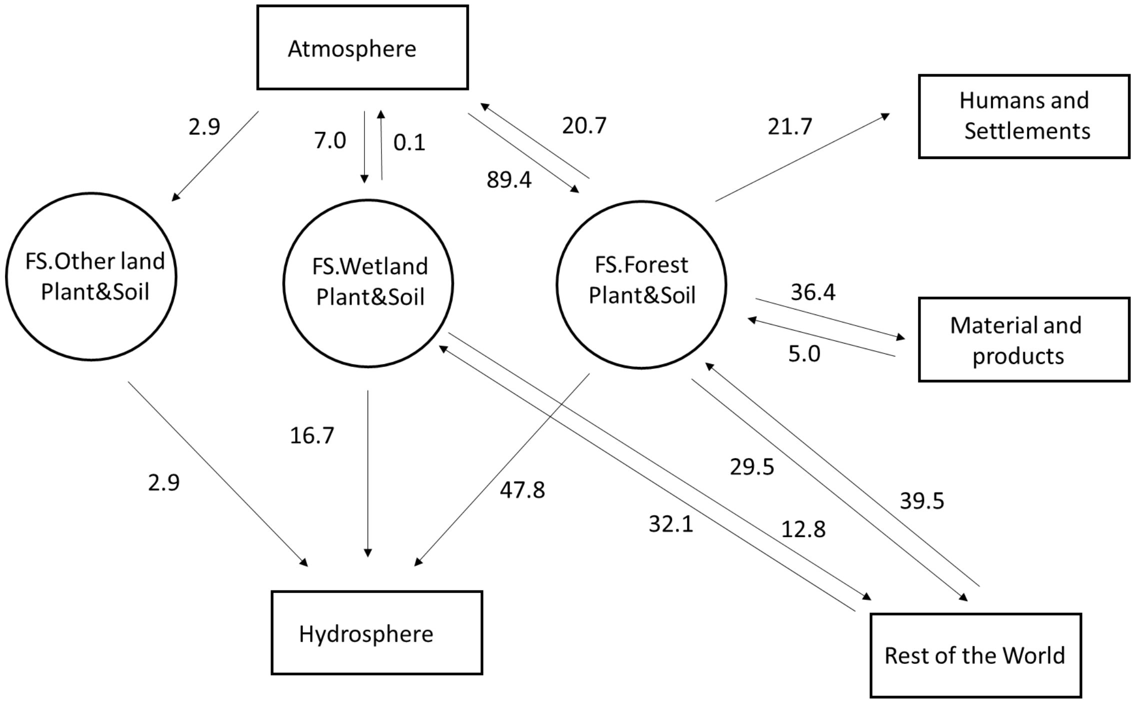

Figure 2. Flows of reactive nitrogen (in kt N) between the "Forest and semi-natural vegetation" pool and the other pools in the Swedish national nitrogen budget and the rest of the world in 2015.

Deposition of reactive nitrogen

The calculation of deposition of reactive nitrogen in Sweden for year 2015 was carried out by SMHI when constructing the Atmosphere part of the Swedish NNB (Moldan et al., in prep.) as follows:

AT – FS.FO: 89.4 kt N

AT – FS.WL: 7.0 kt N

AT – FS.OL: 2.9 kt N

The sum of 99.3 kt N deposited on the area included in FS pool represents 63% of the total Nr deposition in Sweden of 158.7 kt N (Moldan et al., in prep.).

Nitrogen fixation

Ranges of typical N-fixation rates in natural ecosystems are provided in Table 5 in Annex 4. We used the area of forests in Sweden and the N -fixation rate of 1.5 kg N $ha^{-1}a^{-1}$. We chose the ecosystem type "Boreal forests and boreal woodland" and the N-fixation rate at the lower end of the given range as this was a recommendation given in Annex 4.

AT – FS.FO: 39.5 kt N

The N-fixation rate for wetland of 1 g N m^{-2} a^{-1} (10 kg N $ha^{-1}a^{-1}$) is taken from Table 23-1 chapter 23 in Biology of the Nitrogen Cycle (van Cleemput et al., 2007). This is also the same fixation rate as used in the German NNB (UBA, 2020).

AT – FS.WL: 32.1 kt N

N-fixation and denitrification in the "Other land" compartment is considered negligible, as mentioned in Annex 4.

Fertilization

The addition of fertilizer on forest soil is in most countries not a common practice and is therefore not included in the TFRN budget calculations in the TFRN methodology. In Sweden, however, this is an established practice, and it is reported both nationally as well as in the reporting on greenhouse gas emission inventories, and it is therefore included in the Swedish N budget for FO.

The yearly area of fertilized forest can be found in the Statistics database at Skogsstyrelsen (https://www.skogsstyrelsen.se/statistik/statistikdatabas/) and is part of the official statistics for Sweden. During 2015, 33 200 ha of the forested area was fertilized. A standard nitrogen (N) dose in forest fertilization is 150 kg N ha^{-1}. This gives an addition to FO for 2015 due to forest fertilization of:

MP – FS.FO: 5.0 kt N

A small percentage of the added fertilizer is assumed to be emitted to the atmosphere in the form of N_2O. This amount is included in the total N_2O emission from forests as discussed in the next section.

Denitrification

The emissions of N_2 due to denitrification in forest and wetland areas are N-flows out of these compartments since it originates from Nr. However, since N_2 is inert, this flow will not enter the Atmosphere budget in the same way as N-fixation only appears as an input of Nr to the relevant pools but is not considered as a loss from the Atmosphere either.

The emissions of N_2O and NO from FS will enter the Atmosphere pool. Denitrification (and N-fixation) in the Other land compartment is considered negligible following the methodology in Annex 4 and was therefore set to zero.

N_2O and NO

Annex 4 provides a table of country specific estimates of N_2O and NO emissions for forested areas (Kesik et al., 2005) and common values of N_2O emission rates from different types of wetlands. Kesik et al. (2005) used a GIS-coupled process-oriented model. The model was evaluated against measurement data from 19 different field sites across Europe and one site in the USA, however none of these sites were located in Sweden. The table in Annex 4 presents simulated emissions using meteorology for three different years from Kesik et al. (2005). While the simulated N_2O rate for Sweden, 0.66 kg N $ha^{-1}a^{-1}$, is similar as the rate applied for instance in Finland, the NO rates, 1.12 kg N $ha^{-1}a^{-1}$, are much higher. Kesik et al. (2005) noted that these high rates in Sweden were not confirmed by field measurements at the time and hence concluded that the model could have overestimated the NO production by chemo-denitrification. Kesik et al. (2006) used the same GIS-coupled biogeochemical model with some modifications (length of simulation, simulated area, climate data) and found an average emission rate for the years 1991-2000 of N_2O of 0.60 kg N $ha^{-1}a^{-1}$ and NO rate of 0.71 kg N $ha^{-1}a^{-1}$ for Sweden. While the N_2O rate is similar to Kesik et al. (2005), the NO rate is substantially lower. There seems to have been no development/change of N processes in the model, so the difference is more likely due to other parameters and it is difficult to say what NO-rate, if any of them, would be more appropriate to use for Sweden. We have chosen to use the calculated long-term emission rates for N_2O from the more recent Kesik et al. (2006) study since it would likely be less impacted by non-typical meteorological years. For the NO-emission rate we have chosen not to use the values suggested by Annex 4, nor Kesik et al. (2006), (1.12 and 0.71 kg N $ha^{-1}a^{-1,}$ respectively), as these are likely to be overestimated as discussed above. To have a more realistic default value we have chosen to use the NO-rate suggested in the Swiss N-budget of 0.11 kg N $ha^{-1}a^{-1}$ (Heldstab et al., 2010). The N_2 and N_2O rates from the same study (4.7 kg N $ha^{-1}a^{-1}$ and 0.86 kg N $ha^{-1}a^{-1}$, respectively) are higher than the ones we have chosen for Sweden, which is consistent with the fact that in Switzerland there is much higher N-deposition than in Sweden.

Using the average of the estimated emission rates for forested land in Sweden in Kesik et al. (2006) for the N_2O rate = 0.60 kg N $ha^{-1}a^{-1}$ and the NO rate = 0.11 kg N $ha^{-1}a^{-1}$ from the Swiss N-budget results in an emission from the forest of 15.8 + 2.6 = 18.4 kt N. Anthropogenic processes such as land use change and fertilization can also lead to emissions of N_2O. This is included in the Swedish reporting of anthropogenic emissions of greenhouse gases, and for 2015 the reported emission from forest land is 2.3 kt N (www.statistikdatabasen.scb.se). In total the emission of reactive nitrogen from forest land to the atmosphere is:

FS.FO – AT: 15.8 + 2.6 + 2.3 = 20.7 kt N

To estimate the emission of N_2O for Swedish wetlands, we assumed that 1% of the denitrification from wetlands (described in the next section) is emissions of N_2O. The Swedish reported anthropogenic emissions (due to e.g. peat extraction) of N_2O for 2015 for wetlands is 0.003 kt N (www.statistikdatabasen.scb.se). In total the emissions of reactive nitrogen from Swedish wetlands in 2015 to the atmosphere is:

FS.WL – AT: 0.1 + 0.003 = 0.1 kt N

N_2

We chose not to use the default ratio between N_2O and N_2 provided in Annex 4 for estimating N_2 emissions (19.5 +/- 26.8) due to its very large uncertainty. Instead we chose the denitrification rate provided in the German NNB (origin. Andreae et al., 2016) of: 1.1 kg N ha^{-1} a^{-1}, i.e. at the lower end of the ration suggested in Annex 4, but within the uncertainty interval. This gives an outflow of N_2 from forest soils of:

FS.FO – out: 29.0 kt N

For wetlands we used a denitrification factor of 0.4 g N m^{-2} a^{-1} (4 kg N $ha^{-1}a^{-1}$) based on Table 23-1 in Chapter 23 in the book Biology of the Nitrogen Cycle (van Cleemput et al., 2007). That gives an outflow of:

FS.WL – out: 12.8 kt N

Leaching and runoff

As the basis for Sweden's national reporting to the Helcom "Pollution Load Compilation 6 - PLC6" (Ejhed et al., 2016), and also to support national water management, land-based sources of nitrogen- and phosphorus loads to surface waters and subsequently to the sea for the year 2014 were evaluated for the whole Sweden. This includes estimates of the total load of Nr from forested land as well as wetland and other land. These data are used in the Swedish NNB for the Hydrosphere (Stadmark et al., 2020.). In the PLC6 report, the N-loads for wetland and other land are reported together.

FS.FO – HY.SW: 47.8 kt N

FS.WL+OL – HY.SW: 19.6 kt N

The flow of N in runoff from agricultural land into wetland (AG – FS.WL), as suggested in the Annex, will not be specified in the FS pool; instead it has been included in the total runoff from agricultural land to surface waters (Stadmark et al., 2020).

Harvested biomass

The volume of harvested biomass from forests is reported yearly in the Swedish official statistics (e.g. Sveriges officiella statistiska meddelanden, JO0312 SM 1601, Bruttoavverkning 2015) and can also be found in the EUROSTAT database (https://ec.europa.eu/eurostat/home). For 2015, the net removal of biomass in Sweden was 74.3 million m^3 under bark (89.1 million m^3 over bark).

To calculate the amount of N that is removed from the FS.FO compartment by harvesting, at a minimum complexity level, the density and volume of biomass removals and the N-content in different tree parts must be estimated.

A crucial aspect is the choice of value for the N-content of the biomass. Table 16 in Annex 4 lists a range of N-contents depending on tree types and tree compartments (foliage, branches, stems, course roots, fine roots). The biomass removal volumes reported by Sweden do include the subcategories Coniferous and Non-coniferous, however, division into separate tree compartments is not done. Annex 4 suggests using the value for the whole tree which for Sweden would mean 3.4 kg/t for coniferous and 4.3 kg/t for non-coniferous trees. In comparison, the N-content for stems are much lower (1.2 kg/t and 1.4 kg/t for coniferous and non-coniferous respectively). We have chosen to use the more conservative estimates for the roundwood removals and whole tree N-content for the fuel wood removals. To convert from the volume of the removals to the weight, we have followed the suggestion in Annex 4 and used the average wood density from Table 15 (0.45 t m^{-3}). That value was used in the calculations for all types of biomass. The total outtake (including bark) from FS.FO in 2015 using the density and N-contents described is: **58.5 kt N.**

Annex 4 suggests dividing the outflow of N from harvesting from the FS-pool into three flows: (1) fuel wood removals for domestic use, (2) industrial roundwood removals for domestic use and (3) export of industrial round wood and fuel wood.

In the statistics collected from the Swedish Official Statistics and EUROSTAT, the removal is divided into two main categories: firewood and industrial roundwood. Industrial roundwood removal is then further divided into: sawlogs and veneer logs, pulpwood and other industrial roundwood.

The production of industrial roundwood (excluding export) is calculated to be:

FS.FO – MP.OP: 36.4 kt N

In the statistics the roundwood production is presented as the volume under bark. During the logging, however, the stems are harvested with the bark on and thus the bark is removed from the forest. The bark is assumed to be used for heating as is the common practice e.g. in the pulp industry. The same density and N-content as for the stem wood are used. Some reports suggest a higher N-content in bark (e.g. Hellsten et al., 2013 but they also found lower N-content in the stems than used here), while another (Hellsten et al., 2008, IVL report B1798) use a very similar N-content of stem & bark of 1.1 kg t^{-1} for mixed coniferous trees.

FS.FO – HS.MW: 7.3 kt N

For calculating the flow of N due to the production of Fuel wood (including wood for charcoal) excluding wood for export, the same density as for the roundwood is used but with the N-content for the whole tree from Table 16 in Annex 4. Here we assume that the bark is also used as fuel and so the calculation uses the reported volumes over bark. We have assumed that the bark has not been removed on the exported fuel wood.

FS.FO – HS.MW: 14.4 kt N

The export of industrial roundwood and fuel wood for Sweden in 2015 was obtained from the EUROSTAT database. For the export of fuel wood, the division into the subcategories coniferous and non-coniferous is not available until 2017, so an average N-content for coniferous and non-coniferous stems are used. Also, the exported fuel wood is reported under bark and therefore a factor of 1.2 is used to get the total volume. We also assume that the industrial roundwood is exported with bark. The export of Nr is a flow to the “Rest of the World” (RoW) pool.

FS.FO – RoW: 0.5 kt N

According to Annex 4, the Nr flow from FS.FO to the RoW is either directly (export of round wood and fuel wood) or as a flow from FS.FO to MP and then to RoW (several other products). In the EUROSTAT database the export of fuel wood and industrial roundwood are reported as basic products. Included in this category are also Wood chips, particles and residues, Wood pellets and other agglomerates, Wood charcoal and recovered wood (from 2017 and onwards). These flows from FS.FO are not considered by Annex 4 as a direct flow to RoW and therefore have not been specified here. The export from FS.FO to RoW also does not include the much larger Swedish export of sawn wood (12.8 million m^3 for 2015), wood pulp and paper and paper board. These are listed in the EUROSTAT database as primary products. These flows will also be included as flows from MP.OP to RoW.

The Nr flows to and from the three sub-pools

Sweden is a forest-rich country with the largest forest area within EU expressed in hectares and second highest (after Finland) area as a percentage of the country. The FS pool is dominated by forests and the three land-use categories considered in the FS pool together amount to 71% of the country area (Figure 3).

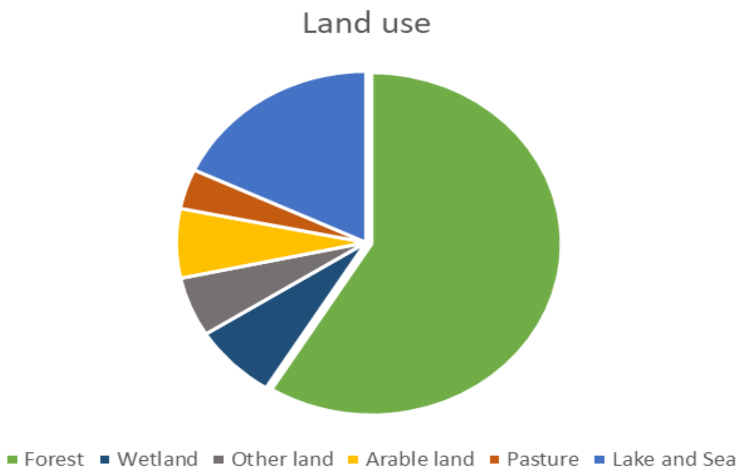

Figure 3. Land use in Sweden divided into six major categories covering >99% of the country. The "Forest and Seminatural vegetation" pool of the Swedish NNB considers Forests (26.3 M ha), Wetlands (3.2 M ha) and Other land (non-agricultural land, mostly mountains, 2.5 M ha). The three categories combined cover 71% of the country's surface area.

Sub-pool Forest (FS.FO)

The N flows to the FO pool were atmospheric deposition, biological nitrogen fixation and fertilization with N-containing fertilizers, a common practice to increase timber production. The three inflows combined were 133.9 kt N. As outflows we considered production of roundwood, runoff leaching, denitrification (as N_2 and as N_2O), production of biomass for energy production and wood production for export (Figure 4). The outputs amounted to 156.0 kt N, all numbers representing year 2015. The Nr flow associated with the N-fertilization has been added to the list of major Nr flows defined in the Annex 4 since fertilizing forests with N is a common practice in Sweden and the associated Nr flow is non-trivial.

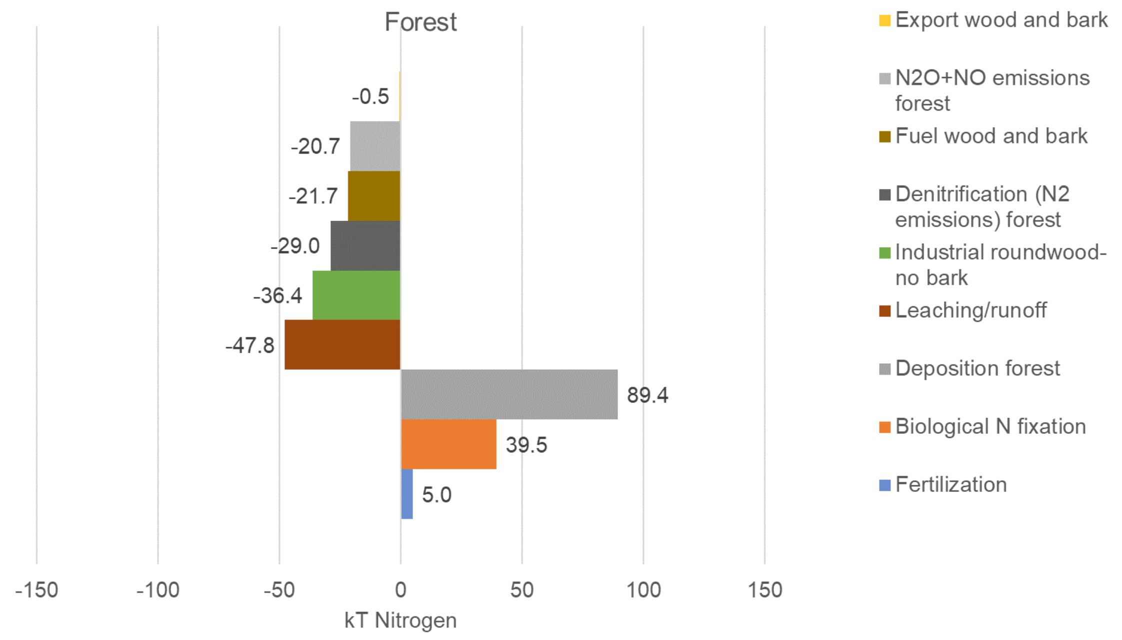

Figure 4. Inflows and outflows of Nr to the sub-pool Forest.

The budget for FS.FO is not quite balanced, with inputs of 133.9 kt N and outputs of 156.0 kt N. Due to the large uncertainties in the quantification of several parts of the budget (e.g. nitrification rates) we are not confident to suggest that the difference represents a change (a decrease) in N stock. Also, reported estimates of C-stocks for forests (http://www.fao.org/3/cb0063en/cb0063en.pdf), as discussed later in the report, suggest a stock increase rather than a decrease.

Other Land (FS.OL)

The sub-pool OL comprises mountainous areas not covered by forest which is a land use type of about 6% of Sweden's area. According to Annex 4, the FS.OL has only one quantitatively significant inflow and one outflow, that is atmospheric deposition and runoff/leaching (Figure 5). As discussed above, the leaching has been calculated for wetlands (FS.WL) and FS.OL together, without distinguishing between the two. To split the leaching between the two sub-pools we assumed that there is no change in Nr stock in the FS.OL. Given that FS.OL represents a land area with little soil and sparse vegetation, the total stock of Nr ought to be small and with no evidence for any change of the stock, this assumption appears to be reasonable at least quantitatively. Therefore, the leaching from FS.OL was set as the same as the atmospheric deposition (the total leaching for both FS.WL and FS.OL subtracted with the deposition to FS.OL is then assumed to be the leaching from FS.WL).

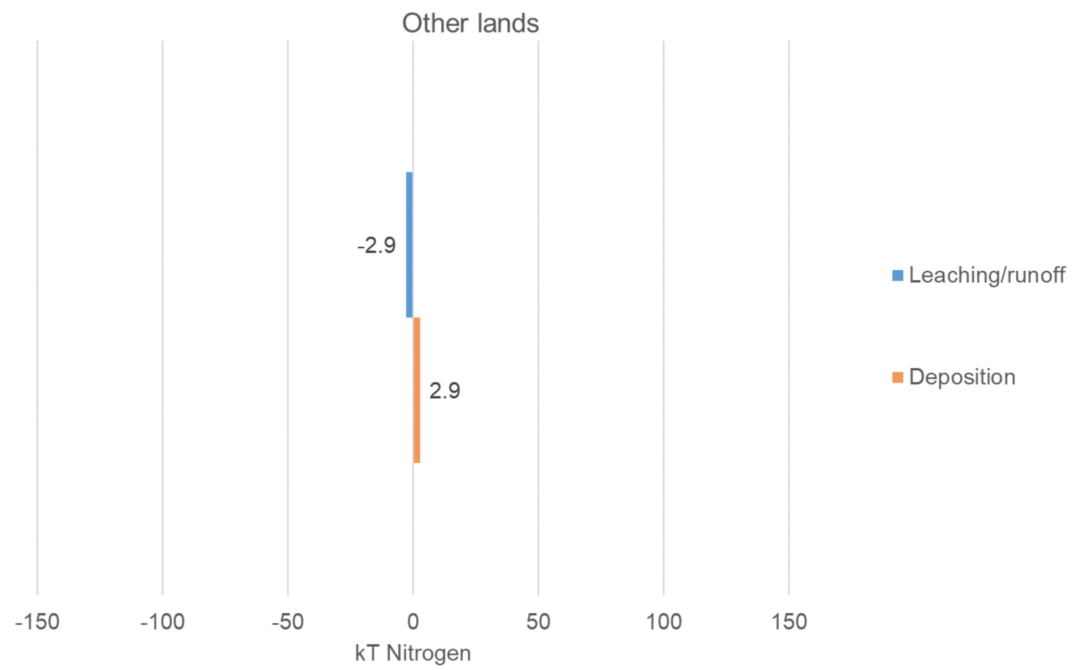

Figure 5. Inflow and outflow of Nr to the sub-pool Other land.

Wetlands (FS.WL)

The inflows to the wetlands amounted to 39.1 kt N and the outflow to 29.6 kt N (Figure 6). N-fixation is by far the largest source of N; more than 4 times larger than atmospheric deposition. The largest outflow is due to leaching/runoff, closely followed by denitrification. There is a variation of wetland types and wetlands are distributed over a large deposition and climate gradient in Sweden. The assumed fixed rates of biological fixation and denitrification are an over-simplification and a source of uncertainty, which is, however, difficult to resolve within the scope of this study.

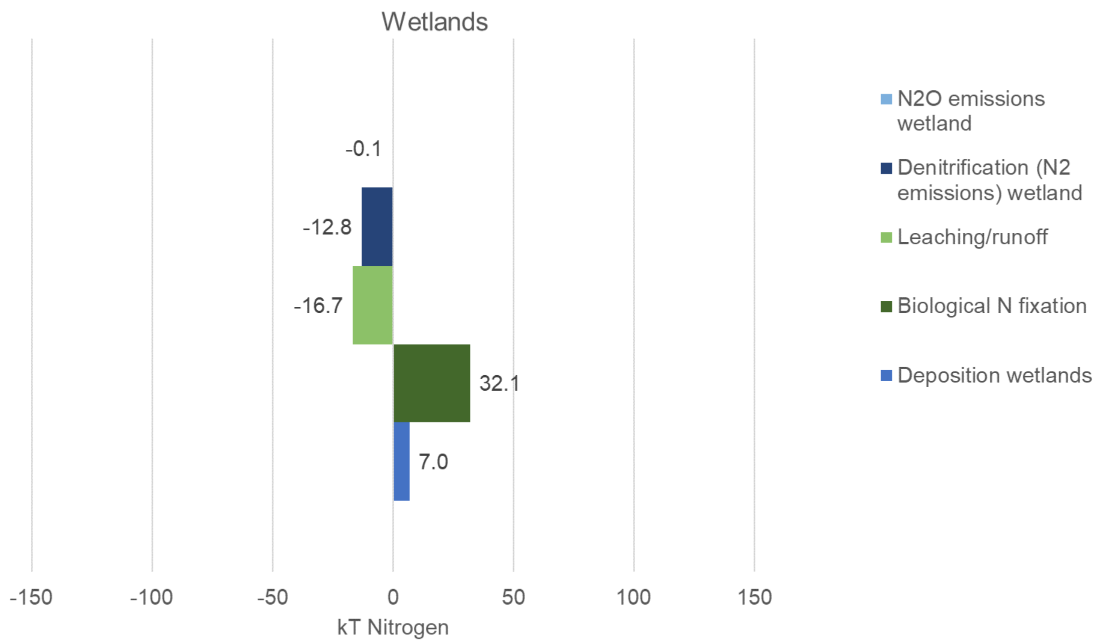

Figure 6. Inflows and outflows of Nr to the sub-pool Wetlands.

Relative to the Annex 4 methodology we did not include the lateral leaching of Nr from Agriculture to the FS pool. Instead all leaching from agriculture is an input to the Hydrosphere pool (Stadmark et al., 2020) with no direct transfer to the FS pool.

Stock and stock changes

Forest

To calculate the N stock and changes in stock in forest land in Sweden, reported C-budgets for different compartments together with C/N-ratios were used. Sweden submits data for the compilation of the periodical Global Forest Resources Assessments (FRA) undertaken by the Food and Agriculture Organization (FAO) of the UN (http://www.fao.org/forest-resources-assessment/en/). Included in this reporting is the C-stock of forest biomass and soil. The C-data is taken from the Swedish Country report for the 2020 Assessment (http://www.fao.org/3/cb0063en/cb0063en.pdf, Table 2d) and is calculated to total C-stock for the actual forest area (26.3 Mha).

In forest and seminatural ecosystems there is a rather large variability of the C/N ratios across the various ecosystem parts. In literature it is common to express C/N either as a weight ratio (gC/gN) or as a molar ratio (molC/molN). For the purpose of this report we use the ratio by weight. Typically, the compartment with the lowest C/N (i.e. the most N rich) are the soil microbes with C/N<10 and the stem wood is the most N-poor pool with C/N of 400 – 500. There is also a variability within the same compartment for e.g. different tree species or soil types. However, there is also a degree of consistency in the published measured C/N, especially when comparing mean values from studies which summarize C/N across multiple sites or across a region. Nadelhoffer et al. (1999) summarized available C/N estimates to two mean values: 500 for trees and 30 for soils.

While these are highly reasonable numbers for global estimates, we used a combination of several studies focused on Europe in general and Scandinavia in particular. DeVries et al (2006) used ICP Forests plots and measured C/N in the organic part of the soil (30 – 40), the top part of the mineral soil (20 – 30) and trees above ground (400 – 500). Gundersen et al. (1998) has provided more detailed measurements from conifer forests in Denmark for tree stems including bark (325), canopy (65), below ground and stumps (65), organic soil (33) and mineral soil (29). Kjønaas and Wright (1998) estimated the C/N for the forest at Gårdsjön (Sweden) in stems to be 288 and 52 in the active part of plants (canopy). They also provided an average C/N for conifer forest litter of 52.

The C/N ratios reported in literature did not follow a uniform protocol in dividing the ecosystems into compartments. Some studies provide C/N for whole trees, other of above- and below ground part of the trees. Furthermore, division between litterfall and dead wood is not done in a consistent manner, neither is division between organic soil, mineral soil and the whole soil profile. In addition, the ecosystem compartments with measured C/N are not divided in the same manner as when reporting C stocks. However, despite these obstacles and uncertainties, the measured and published C/N ratios do provide a relatively robust and transparent way to convert the published estimates of C stocks (http://www.fao.org/3/cb0063en/cb0063en.pdf, Table 2d Carbon stock) into N stocks.

Table 1. Carbon stock in forest for Sweden 2010, 2015 and 2020 and calculated N stock for year 2015 using C/N ratios for the individual compartments. Categories are according to Forest Resource Assessment (FRA). Units: millions of tonnes. (Source: http://www.fao.org/3/cb0063en/cb0063en.pdf)

FRA Categories	2010	2015	2020	N 2015	C/N
Carbon in above-ground biomass	905.0	934.2	954.2	6.2	151
Carbon in below-ground biomass	304.9	313.9	321.0	4.8	65
Subtotal Living biomass:	***1 209.9***	***1 248.0***	***1 275.2***	***11.0***	***113***
Carbon in dead wood	58.5	62.9	68.2	0.2	400
Carbon in litter	635.9	683.5	683.5	10.5	65
Subtotal Dead wood and litter:	***694.3***	***746.5***	***751.7***	***10.7***	***70***
Soil carbon	1 457.1	1 474.0	1 474.0	46.5	32
Total:	**3 361.3**	**3 468.5**	**3 500.8**	**68.2**	**51**

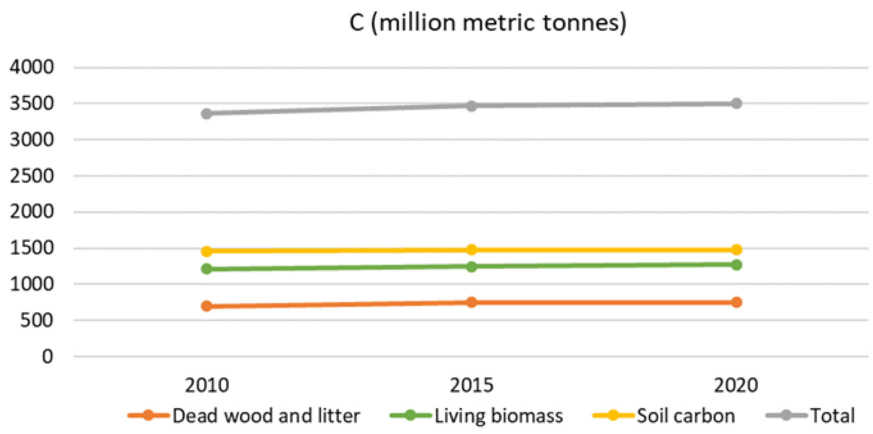

Figure 7. Carbon stock in forest compartments 2010, 2015 and 2020, unit: million tonnes. Calculated with data from http://www.fao.org/3/cb0063en/cb0063en.pdf.

Table 1 and Figure 7 indicate an increase in total C stock in forests from 2010 to 2020 with an increase from 3361 MT C in 2010 to 3501 MT C in 2020. All compartments increase between 2010 and 2015. While the C stock in living biomass continue to increase up to 2020, the C stock in soil and dead wood and litter stays essentially the same after 2015. C/N ratios are typically stable over time as both the C and N stocks are large relative to annual C and N flows in all relevant ecosystem compartments. Given that the soil and biomass C/N ratios did not change over time, the reported increase in C stock between 2010 and 2020 would require an annual flow of 186 kt N, close to the total input to the FS pool. The largest change in C-stock has been reported in litter, followed by soil. Comparing the changes in stock between 2015 and 2020, the annual flow of N needed to support the C accumulation would be substantially lower (51 kt N) since there is little change in C stock for litter and soil between these years. While the exact amount of N needed to support the reported build-up of the C-stock could be discussed, the order of magnitude is striking. The inputs of N calculated in this report would have to double (almost exactly) to support this process and we have no explanation to what the origin of N to enable this process in that case is. The discrepancy between the reported build-up of C stock in the FS pool and the availability of N to make that possible illustrates the benefits of looking at the C and N flows in combination since these are intimately coupled. We hope that the question will be re-visited in future studies.

There are several potential additional flows which are not considered here. In the reporting of C stock in the soil, only the upper 50 cm is considered while in reality the soils are in many cases deeper and there is potential for C transfer both from mineral soil up by the roots and down from organic layer (and from the uppermost mineral soil) to mineral soil deeper down. The transfer from (or to) the deeper mineral soil is another flow of N if the system limit is set to 50 cm into the soil profile.

Wetlands

The stock and stock changes of nitrogen in wetlands have not been possible to estimate in this report. Nahlik & Fennessy (2016) stated that “Wetland soils contain some of the highest stores of soil carbon in the biosphere. However, there is little understanding of the quantity and distribution of the carbon stored in our remaining wetlands or of the potential effects of human disturbance in these stocks“. The estimates of carbon vary from 30 kg m^{-2} (1-120 cm, Nahlik & Fennessy, 2016) in the U.S. to 42 kg m^{-2} in northern peatlands (1-100 cm, Villa & Bernal, 2018) and 66 kg C m^{-2} in all temperate and tropical wetlands (Villa & Bernal, 2018). There is a large variability of C/N ratios for different wetlands and wetland compartments. Mazierz et al. (2019) refer to studies where weight C/N ratios between 9 and 145 have been reported for soils (1-20 cm) in natural freshwater wetlands and C/N ratios from 12 to 49 in the plant biomass. All in all, the available data on Swedish wetland volume, carbon content in the wetlands and the C/N ratios on different compartments is too scarce or too unprecise to allow an estimate on the N stock in Swedish wetlands and the annual stock change. It is, however, important to keep the C and N stock in wetlands in mind in the context of NNB since the size of the stock is most likely very substantial. Just to illustrate the order of magnitude: there are 3.2 Mha of wetlands in Sweden. If we, for the sake of argument, assume C storage of 50 kg C m^{-2} and a C/N ratio of 30, the resulting N stock in FS.WL would be ca 53 million tonnes N, which is of similar size as the total N stock in all Swedish forests (Table 1).

Conclusion

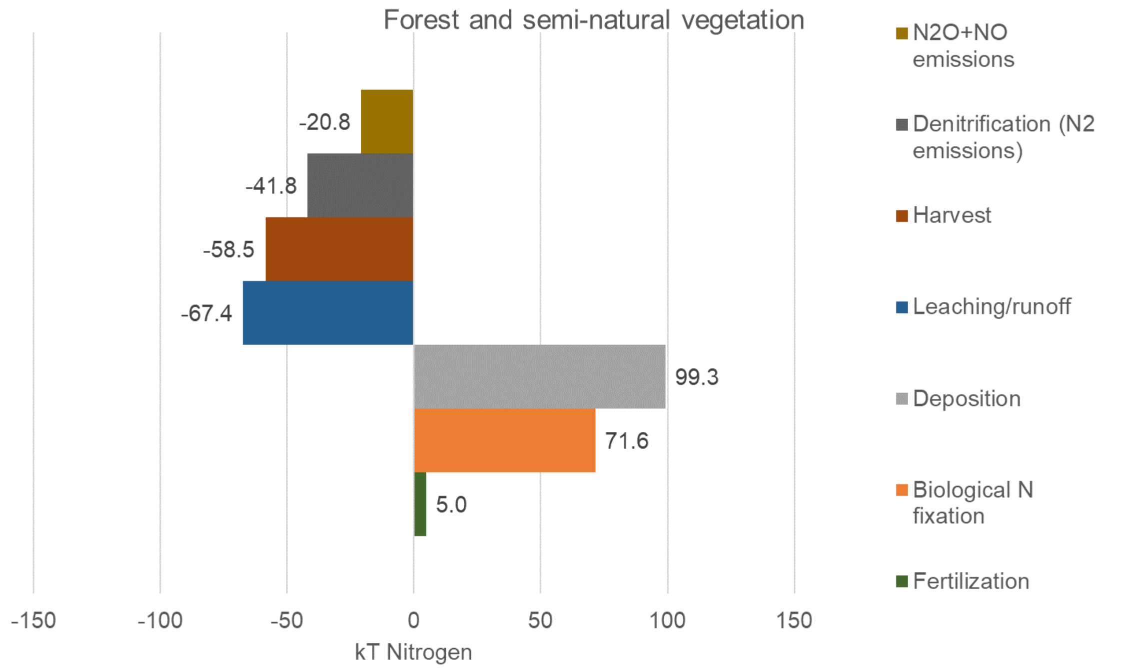

Figure 8. Inflows and outflows of Nr for the "Forest and semi-natural vegetation" pool.

In total, the "Forest and semi-natural vegetation" pool has inflows of 175.8 kt N and outflows of 188.6 kt N. The largest inflow in the pool comes from atmospheric deposition and the largest outflow from the pool is via leaching/runoff. The FS.FO subpool budget has the biggest impact on the flows of the overall FS-pool. Forestry is an important industry in Sweden and the flow of N from FS:FO due to harvest is the second largest outflow from the entire FS-pool. FS.WL has a comparatively large inflow of Nr due to biological fixation and the calculations in this report show that biological fixation is a much larger source of N than atmospheric deposition for FS.WL. FS.OL has small contributions to the flows of the FS-pool and only two flows: leaching/runoff and deposition.

There are many sources of uncertainties in the calculations, perhaps the most evident are the denitrification and fixation rates. Another large uncertainty is in the choice of the N-content used in the calculations of N-outflow due to biomass harvesting. While the estimations of the amount of biomass removed from the forest is most likely fairly robust, the choice of values representing the N-content of different parts of the trees can significantly change the total amount. Choosing the highest published biomass N-contents would almost triple the outflow of N presented in this report. Another question is the discrepancy between the reported build-up of C stock in the FS pool and the availability of N to make that possible. During this work to construct a budget for the "Forest and semi-natural vegetation" pool for the Swedish NNB it became clear that there are several issues that will have to be further investigated and improved in the future. One outstanding issue is the need to connect the NNB of Forest and semi-natural vegetation with the carbon budget since the cycling of the two elements is intimately coupled.

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