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Item 4 (b) of the provisional agenda
Review of the implementation of the 2020-2021 workplan: policy

Assessment report on ammonia[*]

Summary

The present report was prepared by the Task Force on Integrated Assessment Modelling in cooperation with the Task Force on Measurements and Modelling and the Task Force on Reactive Nitrogen, in accordance with item 1.1.3.3 of the 2020–2021 workplan for the implementation of the Convention (ECE/EB.AIR/144/Add.2). The Working Group on Strategies and Review welcomed the report at its fifty-ninth session (Geneva, 18-21 May 2021) and forwarded it to the Executive Body for consideration at its forty-first session.

The report gives a concise and policy-oriented overview of ammonia that brings together key data and research findings from various studies. Both ammonia and nitrogen oxide emissions contribute to eutrophication and acidification, as well as to the formation of secondary particulate matter. In the past few decades, policy efforts have been more focused on emission reduction of nitrogen oxides than on ammonia emission reduction. This report aims to contribute to improving understanding of the benefit of ammonia mitigation and to support ratification and implementation of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. The annexes to the present report are included in informal document No. 1 for the session.

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[*] The present document is being issued without formal editing.

I. Summary

1. Ammonia emissions were reduced much less in the past few decades compared to other pollutants such as sulfur and nitrogen oxides. Ammonia is the dominant source of excess nitrogen deposition on vulnerable ecosystems. But ammonia also plays an important role in the exposure of the population to fine particulate matter ($PM_{2.5}$). In and around regions with high livestock densities, ammonia is responsible for more than 50 per cent of the nitrogen deposition and particulate matter exposure. In such regions, the costs of inaction could easily exceed those of taking measures. This environmental damage is not included in the production costs or the prices of meat and dairy products.

2. In order to avoid damage to ecosystems and health, a 30–50 per cent reduction in ammonia emissions is required in areas of the United Nations Economic Commission for Europe (ECE) region with a high density of livestock and use of nitrogen fertilizers. There are sufficient technical abatement options available to reduce emissions of ammonia (up to about 50 per cent reduction), but in some regions (where the most cost-effective measures have already been implemented) a reduction of livestock densities may be inevitable, if legally protected natural habitats are to be safeguarded for the future.

3. Emissions of ammonia to the atmosphere reflect inefficient use of nitrogen nutrients. Covering manure storage and optimal application of manure during the growing season are simple and cheap measures that can also reduce the need for fertilizer use. Low-emission manure application techniques are the most effective step in reducing ammonia emissions. Reduction of emissions from stables with air scrubbers is – given farmers' current profit margins – only affordable for larger farms, but future innovations might reduce the costs. Several options are available for cost-effective reduction of ammonia emissions from urea and other fertilizers. Reduction of ammonia emissions represents an opportunity for more efficient use of nitrogen, with co-benefits for air and water quality, climate, biodiversity and health.

II. Ammonia in Europe

A. Current status and trends

4. There are large regional differences in ammonia emissions in Europe and in the world. Areas with high emission densities correspond with areas with a high loss of biodiversity and a large share of secondary particulate matter in the exposure of population to air pollution both within such areas as well as in nearby regions. Secondary particles play a significant role in transboundary fluxes of air pollution and in air quality in large parts of Europe and North America.

5. In areas with high densities of livestock, emissions per hectare are 3–5 times higher than on average in Europe (see figure I below). Ammonia emissions are mainly caused by manure excretion in stables, manure storage and manure application. Globally, fertilizers are estimated to contribute a similar amount of ammonia as livestock, largely due to urea use.[1] Emissions from fertilizers are lower in Europe because ammonium nitrate-based fertilizers predominate, although use of urea fertilizers has been increasing. A small part (around 10 per cent) of the annual ammonia emissions comes from industry, households and traffic.

6. Excessive nitrogen deposition can contribute to the loss of plant species, butterflies and birds (see figure II below).[2] In Europe, this is even the case in areas with high densities of traffic and emissions of nitrogen oxides. The higher the spatial resolution of ecosystem

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[1] Uwizeye, A., de Boer, I.J.M., Opio, C.I. et al. (2020) Nitrogen emissions along global livestock supply chains. Nat Food 1, 437–446 https://doi.org/10.1038/s43016-020-0113-y.

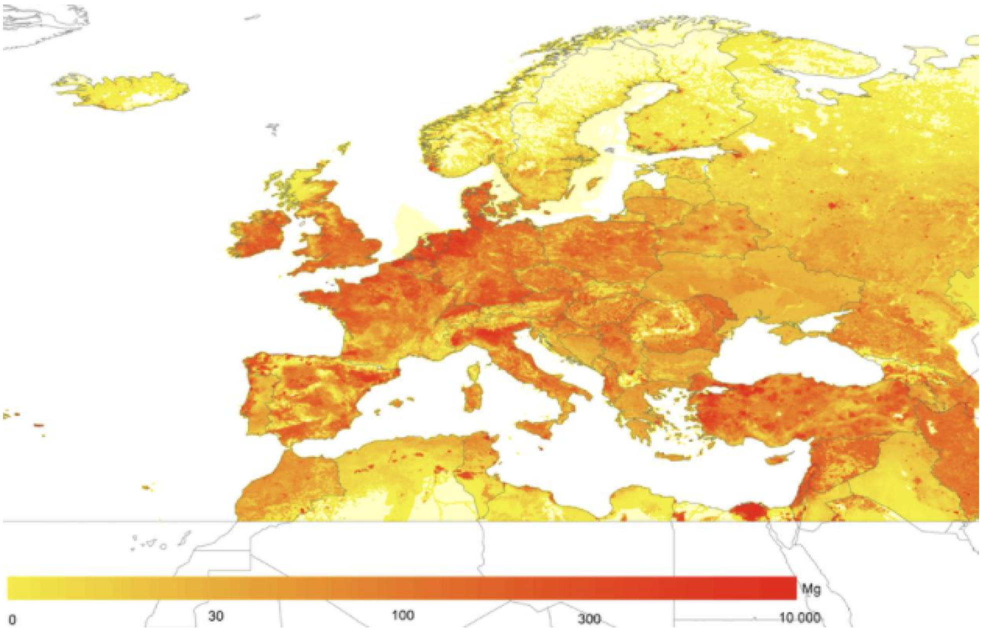
[2] Feest, A , A van Hinsberg, C van Swaay (2014), Nitrogen deposition and the reduction of butterfly biodiversity quality in the Netherlands, Ecological Indicators, Vol 39, p115-119, https://doi.org/10.1016/j.ecolind.2013.12.008; Hendrik M, A van Hinsberg, P Janssen and B de Knegt (eds.) (2016), BIOSCORE 2.0 - A species-by-species model to assess *anthropogenic impacts on terrestrial biodiversity in* Europe, PBL/WUR).

maps, the more sensitive the nature areas that can be detected. Some sensitive plant species and lichens are also affected by direct exposure to high ammonia concentrations. Moreover, ammonia emissions contribute to marine eutrophication, which is especially a problem in the Baltic Sea.

7. Recently, political awareness has increased that ammonia emissions not only lead to a loss of biodiversity, but also contribute significantly to the exposure of the population to particulate matter and the associated health risks.[3] In large areas of Europe, more than half of anthropogenic particulate matter concentrations are not emitted directly, but are formed in the air when ammonia reacts with nitrogen oxides or sulfur dioxide (the so-called secondary particles) (see figure III below). Also, in North America and Asia, the role of ammonia in the formation of particulate matter is getting more attention.[4]

Figure I

Ammonia emissions in 2018 in kg NH_3 per km^2



Source: https://www.ceip.at/the-emep-grid/gridded-emissions/nh3.

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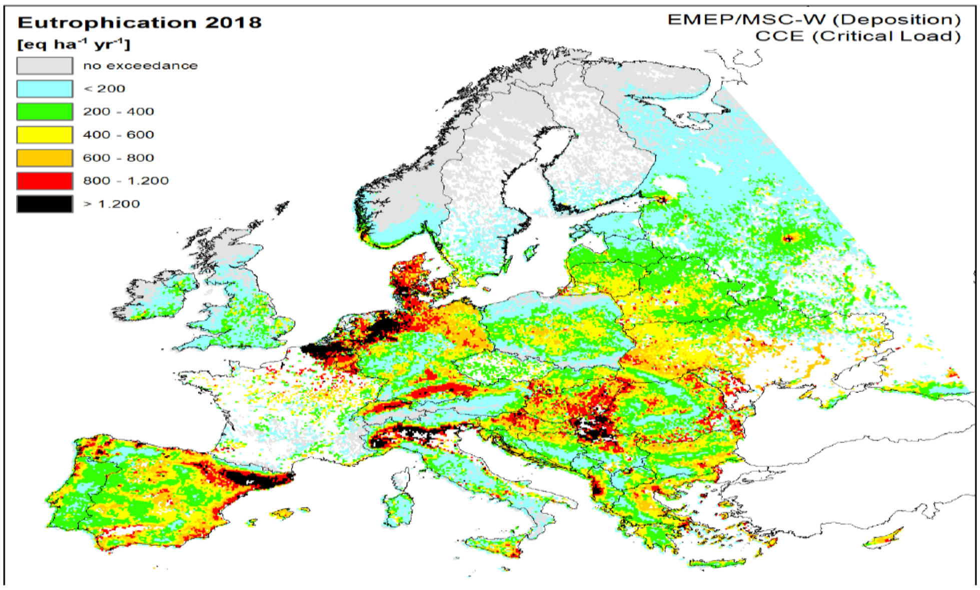
[3] Maas R. and P. Grennfelt (eds) (2016) Towards Cleaner Air, Scientific Assessment Report 2016, UNECE, http://www.unece.org/index.php?id=42861.

[4] Plautz J. (2018), Piercing the haze - Ammonia, a poorly understood smog ingredient, could be key to limiting deadly pollution, Science Magazine Sept 13, 2018; and: Purohit et al, (2019), Mitigation pathways towards national ambient air quality standards in India. Environment International 133: e105147. DOI:10.1016/j.envint.2019.105147.

Figure II

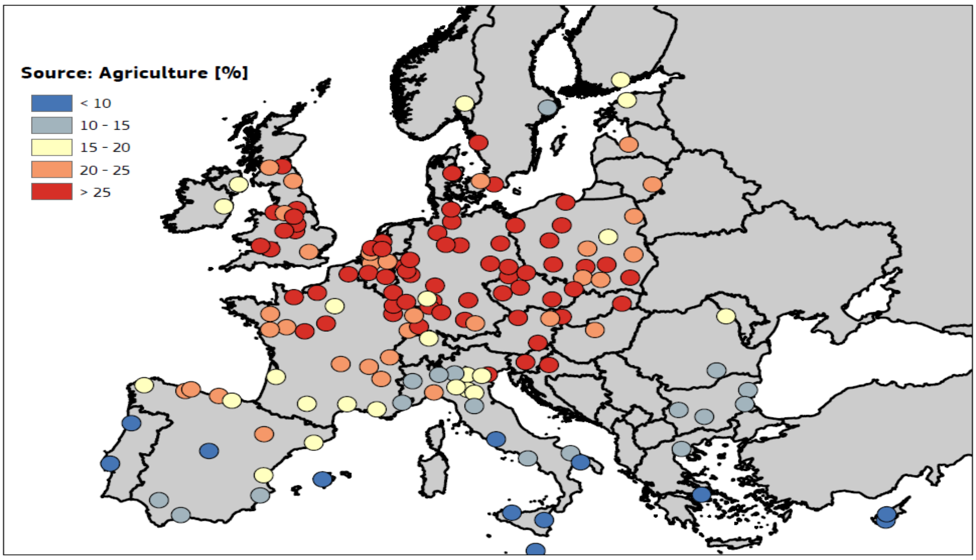
Exceedance of the critical load for nitrogen in 2018



Source: EMEP Meteorological Synthesizing Centre-West and Chemical Coordinating Centre

Figure III

Share of ammonia-related secondary aerosol in urban PM$_{2.5}$-concentrations in 2015



Source: Joint Research Centre (JRC)

8. Figure IV below indicates the origin of particulate matter concentrations in 2009 in cities (measured as PM$_{2.5}$ - particulate matter with a diameter of less than 2.5 micrometres). The light green and dark green bars show the secondary particles (ammonium nitrates and ammonium sulfates, respectively) that are both influenced by ammonia emissions. The pink line in figure IV indicates the World Health Organization (WHO) air quality guideline level of 10 micrograms per m^3.[5] Figure V below shows the source apportionment in Brussels, where, according to the Screening for High Emission Reduction Potentials for Air quality (SHERPA) model of the Joint Research Centre of the European Commission, the largest single source-sector contribution to PM$_{2.5}$ is agriculture, i.e. ammonia emissions. In the Benelux countries and surrounding parts of Germany and France more than 50 per cent of

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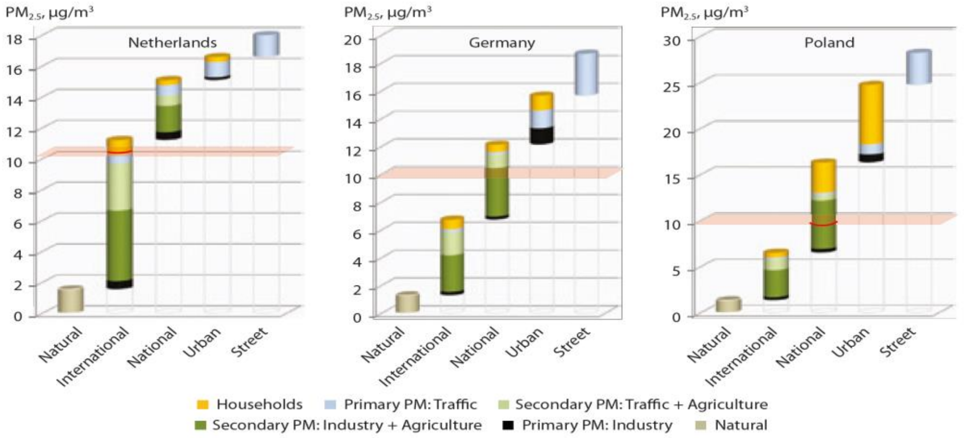
[5] WHO (2006) *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide.*

the average $PM_{2.5}$ concentration consists of secondary particles. According to Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) modelling, foreign sources contribute 70–80 per cent to the secondary $PM_{2.5}$ concentrations in Benelux countries.

Figure IV

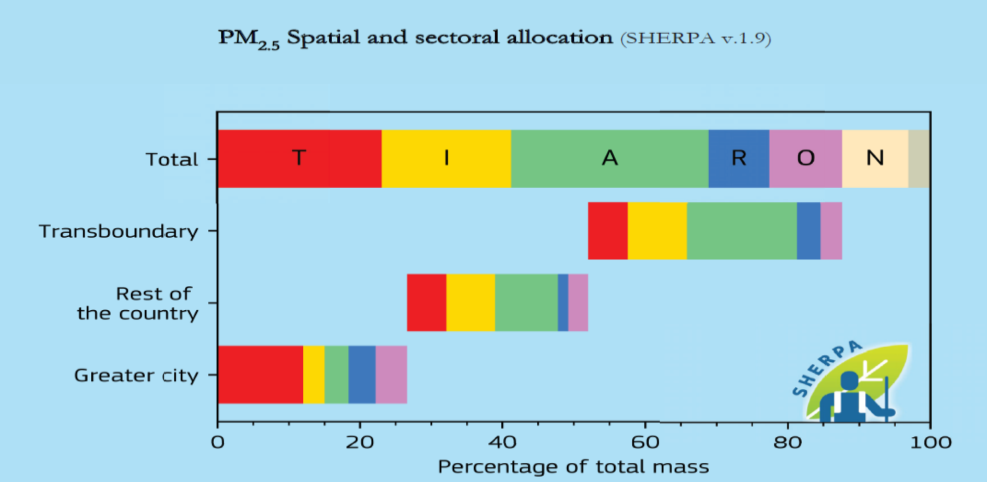
Origin of urban background concentrations of particulate matter in the Netherlands, Germany and Poland according to the Greenhouse Gas-Air Pollution Interactions and Synergies model



Source: International Institute for Applied Systems Analysis (IIASA)

Figure V

Origin of urban background concentrations of particulate matter in Brussels according to the Screening for High Emission Reduction Potentials for Air quality model



Source: JRC, 2017

9. Currently, exceedances of the European Union air quality limit value of particulate matter occur frequently in cities during weeks with dry weather and high ammonia emissions, for example, in early spring when manure that was stored during the winter is applied on agricultural land.[6]

10. Since 2000, only modest reductions of ammonia emissions have been achieved in Europe and North America compared to the reductions of other pollutants like sulfur dioxide (SO_2), nitrogen oxides (NO_x) and primary particulate matter (see figure VI below). According to the EMEP trend report, observations of ammonium concentrations at EMEP

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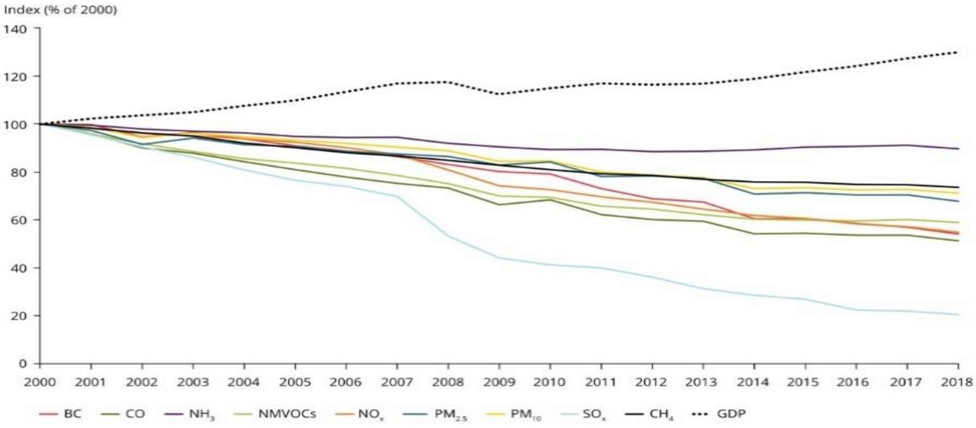
[6] Laboratoire Central de Surveillance de la Qualité de l'Air (2015) Observation et analyse en temps quasi-reel des episodes de pollution particulaire de Mars 2015. Laboratoire Central de Surveillance de la Qualité de l'Air.

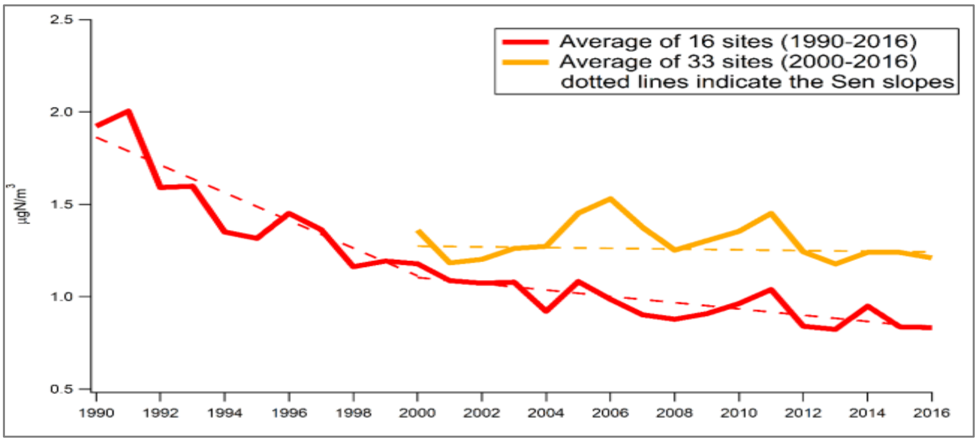
background stations showed no significant downward trend for Europe as a whole after 2000 (see figure VII below),[7] although a significant reduction in particulate matter ammonium concentrations has been observed regionally (for example, a 48 per cent reduction for the United Kingdom of Great Britain and Northern Ireland between 1999 and 2014).[8] This reduction in particulate matter ammonium is estimated to be primarily due to reductions in SO_2 and NO_x emissions, giving ammonia a longer lifetime in the atmosphere, as reflected in a tendency to increasing ammonia concentrations in remote areas.[9]

Figure VI
Trends in European Union-28 emissions, 2000 = 100: ammonia is the second line from the top; Sulfur is the lowest



Source: European Environment Agency (EEA)

Figure VII
Average European reduced nitrogen concentrations in air and aerosols at EMEP-background stations (sum of NH_3 and NH_4 in µgN/m^3)



Source: EMEP Chemical Coordination Centre

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[7] EMEP (2016) Air Pollution trends in the EMEP-region, EMEP/CCC-report 2016/1.

[8] Tang et al. (2018) Drivers for spatial, temporal and long-term trends in atmospheric ammonia and ammonium in the UK, Atmospheric Chemistry and Physics, vol 18 nr 2, https://www.atmos-chem-phys.net/18/705/2018/.

[9] These findings are consistent with earlier comparison of ammonia, ammonium and wet deposition trends across Europe in relation to emissions of ammonia, SO_2 and NO_x in: Bleeker et al. (2009) Linking ammonia emission trends to measured concentrations and deposition of reduced nitrogen at different scales. and: Horváth et al , Fagerli H. and Sutton M.A. (2009) Long-Term Record (1981–2005) of ammonia and ammonium concentrations at K-Puszta Hungary and the effect of sulphur dioxide emission change on measured and modelled concentrations. Chapter 12, in: *Atmospheric Ammonia: Detecting emission changes and environmental impacts* (eds. M.A. Sutton, S. Reis and S.M.H. Baker), pp 181-186, Springer.

Note: Background measurement stations are not representative for areas with high livestock density

11. Emission projections in Europe also indicate that future ammonia emission reductions will be relatively small if these depend only on current legislation, compared to the emission reductions of SO_2, NO_x and primary particulate matter, where substantial commitments to reduce emissions over the period 2020–2030 have been made.[10]

12. The European Union and several countries have defined the WHO guideline value[11] for $PM_{2.5}$ as their long-term target (e.g. see the Clean Air Programme for Europe - EC, 2013). However, from the source apportionment of $PM_{2.5}$ concentrations (see figures IV and V above) it is clear that, in many cities, meeting the WHO air quality guideline value for $PM_{2.5}$ will not be possible without substantial reductions in emissions of ammonia, nitrogen oxides and sulfur dioxide in the wider region. For nitrogen oxides and sulfur dioxides, European Union-wide emission reductions of around 60 per cent (between 2005 and 2030) are an obligation under the revised National Emissions Ceiling Directive,[12] but for ammonia the reduction obligation is only 5 per cent (before 2030) up to 15 per cent (after 2030). There are large variations in emission reduction obligations among countries (see table 1 below). For several countries, the ammonia emission reduction obligation for 2020 is modest and more emission reduction is envisaged for 2030 and beyond.

Table 1

Emission reduction requirements for 2020 and 2030 according to the revised National Emissions Ceiling Directive for selected countries (in percentages of the 2005 level)

	NH3		*NOx*		*SO2*		*Primary PM2.5*	
	2020	2030-NECD	2020	2030-NECD	2020	2030-NECD	2020	2030-NECD
Belgium	2	13	41	59	43	66	20	39
Denmark	24	24	56	68	35	59	33	55
France	5	13	50	69	55	77	27	57
Germany	5	29	39	65	21	58	26	43
Italy	5	16	40	65	35	71	10	40
Netherlands	13	21	45	61	28	53	37	45
United Kingdom	8	16	55	73	59	88	30	46
European Union- 28	6	19	42	63	59	79	22	49

Source: European Union National Emissions Ceiling Directive.

13. The formation of secondary particles can be reduced via emission reduction of either nitrogen oxides and sulfur dioxide or of ammonia, or both. For the formation of a particle of ammonium nitrate in the air, one molecule of ammonia and one molecule of nitrate (or nitric acid) are needed (while two molecules of ammonia will react with one molecule of sulfuric acid to form a particle of ammonium sulfate). Due to decreasing availability of nitrogen oxides and sulfur dioxide, the share of the ammonia emission that is converted into secondary aerosols is decreasing. This is reflected in the increasing ratio of gaseous ammonia to

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[10] European Commission (2013) Proposal for a directive of the European Parliament and of the Council on the reduction of national emissions of certain atmospheric pollutants and amending Directive 2003/35/EC (COM(2013) 920 final).

[11] The WHO advises reducing $PM_{2.5}$ exposure to 10 µg/m^3 as an annual mean.

[12] Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC, *Official Journal of the European Union*, L 344 (2016), 1–31.

particulate ammonium concentrations.[13] Several other changes can be expected, although the net effect of all these remains uncertain. A larger fraction as ammonia is likely to worsen adverse effects on sensitive plant groups.[14] Conversely, overall removal rates of ammonia by the ground (through dry deposition) may decrease, due to the less acidic surface.[15] The net result may be that emitted ammonia has a longer atmospheric residence time, leading to larger ammonia concentrations (Tang et al., 2020) and deposition in locations further away from the sources. However, as ammonium travels further than ammonia, so the net effect on total nitrogen depositions and exceedances of critical loads in remote areas with sensitive ecosystems and low ammonia emissions, for example, in Northern Europe, will likely be negative.

14. What is clear is that ammonia and ammonium nitrate are now dominating the inorganic air pollution load across Europe.[16] While nitrogen deposition may end up having some benefits for carbon sequestration by forest areas distant from agricultural land,[17] it is also expected to come with a cost for sensitive biodiversity.

15. Further emission reductions of ammonia would be required to prevent the exceedance of WHO-guideline values for particulate matter concentrations, as well as avoiding the exceedance of critical loads of ecosystems. In areas with a high density of livestock emission reductions of 30–50 per cent would be required to meet such long-term targets. In addition, it must be recognized that ammonia has substantial local variability, so that protection of natural habitats in the immediate vicinity of ammonia sources may require even larger emissions reductions, or relocation of emitting activities to be more distant from vulnerable habitats.[18]

16. Ammonia emissions are not the only way nitrogen nutrients from agriculture are lost to environment. Other losses of reactive nitrogen are leaching nitrate to groundwater and water streams, emissions of nitrous oxide (N_2O, a potent greenhouse gas) and emissions of nitrogen oxides from agricultural land (see figure VIII below).

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[13] EEA (2018), Report on particulate matter and agriculture; and : Tang et al. (2018) Drivers for spatial, temporal and long-term trends in atmospheric ammonia and ammonium in the UK, Atmospheric Chemistry and Physics, vol 18 nr 2, https://www.atmos-chem-phys.net/18/705/2018/.

[14] Sheppard et al, (2011) Dry deposition of ammonia gas drives species change faster than wet deposition of ammonium ions: evidence from a long-term field manipulation. Global Change Biology 17, 3589-3607. (DOI: 10.1111/j.1365-2486.2011.02478.x).

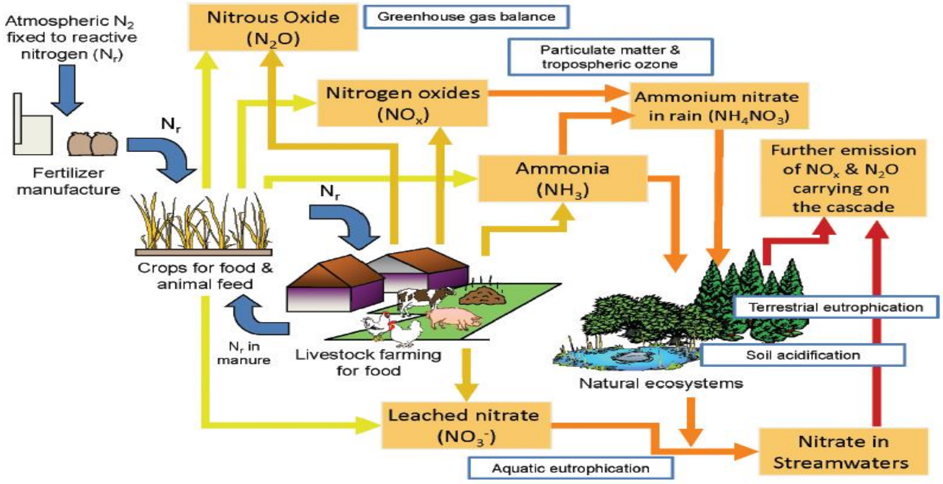
[15] Flechard C., Fowler D., Sutton M.A. and Cape J.N. (1999) Modelling of ammonia and sulphur dioxide exchange over moorland vegetation. Q. J. R. Met. Soc. 125, 2611-2641.

[16] Tang et al. (2020) Pan-European rural atmospheric monitoring network shows dominance of NH_3 gas and NH_4NO_3 aerosol in inorganic pollution load. Atmos. Chem. Phys. Discuss. https://doi.org/10.5194/acp-2020-275.

[17] Flechard, et al, (2020a) Carbon / nitrogen interactions in European forests and semi-natural vegetation. Part I: Fluxes and budgets of carbon, nitrogen and greenhouse gases from ecosystem monitoring and modelling. Biogeosciences 17, 1583-1620, https://doi.org/10.5194/bg-17-1583-2020; and: Flechard et al, (2020b) Carbon / nitrogen interactions in European forests and semi-natural vegetation. Part II: Untangling climatic, edaphic, management and nitrogen deposition effects on carbon sequestration potentials. Biogeosciences 17, 1621-1654. https://doi.org/10.5194/bg-17-1621-2020.

[18] Dragosits U., Theobald M.R., Place C.J., ApSimon H.M., Sutton M.A. (2006) The potential for spatial planning at the landscape level to mitigate the effects of atmospheric ammonia deposition. J. Environ. Sci. & Policy 9, 626-638, and: Loubet et al. (2009) Ammonia deposition near hot spots: processes, models and monitoring methods. Chapter 15, in: Atmospheric Ammonia: Detecting emission changes and environmental impacts (eds. M.A. Sutton, S. Reis and S.M.H. Baker), pp 205-267, Springer.

Figure VIII
Simplified view of the cascade of nitrogen flows from agricultural sources



Source: Summary for Policy Makers of the European Nitrogen Assessment

17. An integrated policy strategy is needed to ensure that ammonia reduction measures do not increase other nitrogen-related problems, and to optimize potential synergies. From a field perspective on its own, ammonia emissions could be reduced with deep injection of manure on grassland, but the risks are increased leaching of nitrates to groundwater or higher emissions of nitrous oxide. In fact, such interactions are more complex than this at farm and landscape scales because the reduced ammonia emissions will result in less nitrous oxide from woodland and nature areas, while reducing ammonia losses offers a nitrogen saving, leading to opportunities to use less fertilizers. If well managed, the net result can be an overall improvement in system efficiency, with less nitrous oxide emission and nitrate leaching at the same time. Such approaches can therefore help progress towards a circular nitrogen economy.[19]

18. Potential synergies and trade-offs can also be found beyond the nitrogen cycle. Losses of other nutrients (e.g. phosphate), methane emissions and carbon sequestration are also linked to changes in the nitrogen cycle. To illustrate this, low nitrogen cattle feed could decrease ammonia emissions, but if this were achieved by increasing the proportion of fibrous, roughage feed, it could enhance methane emissions. Conversely, other practices can give co-benefits, such as through combined anaerobic digestion and low-emission manure spreading, which can help methane and ammonia emissions at the same time (see also annex II to the present document included in informal document No.1 for the fifty-ninth session of the Working Group on Strategies and Review).[20] In order not to cause a shift in the problem but to effectively reduce nitrogen emissions in agriculture, in certain regions there might be no way around reducing the number of livestock and limiting the number of animals per hectare.

B. Sources and abatement measures

19. Manure from livestock farming is responsible for more than 70 per cent of the emissions of ammonia in Europe. The use of mineral fertilizer in agriculture contributes almost 20 per cent to the ammonia emissions. Traffic, industry and people make up the remaining part. In Europe, around 50 per cent of the emissions from livestock come from

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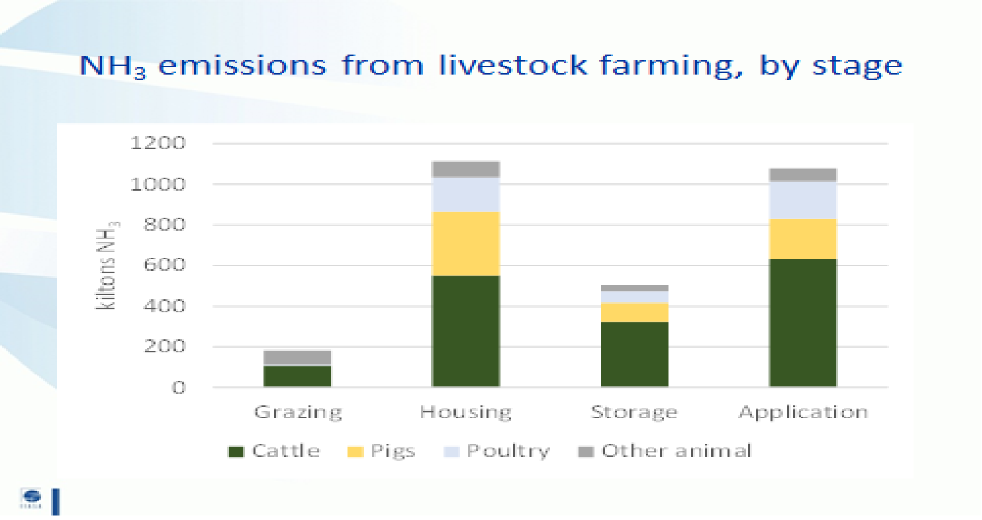
[19] Sutton et al. (2019) The Nitrogen Fix: From nitrogen cycle pollution to nitrogen circular economy. Frontiers 2018/2019: Emerging Issues of Environmental Concern. pp 52-65, United Nations Environment Programme, Nairobi. ISBN: 978-92-807-3737-0.

[20] Dalgaard, et al. (2015) Methane and Ammonia Air Pollution. Policy Brief prepared by the UNECE Task Force on Reactive Nitrogen. http://www.clrtap-tfrn.org/.

cattle, 30 per cent from pigs and 20 per cent from poultry.[21] In some countries new ammonia emission sources e.g. from the application of sewage sludge and of digestates from energy crops, are growing fast.

20. Housing (40 per cent), storage (20 per cent), application (35 per cent) and grazing (5 per cent) are the main stages in the manure-chain that cause ammonia emissions (see figure IX below). These stages are not independent of each other. E.g., cleaner animal housing means more nitrogen is kept in the manure. Coverage of manure storage has the same effect. It means that potentially more ammonia could be emitted during application on land. Therefore, low-emission manure application is the cornerstone of an effective ammonia abatement strategy, and – as was also shown in studies in e.g. Germany and France – the measure with the largest emission reduction potential. In Germany, low-emission manure application would cover almost 60 per cent of the total technical abatement potential.[22] In France, the Environment and Energy Management Agency estimated that direct incorporation and injection will form 60 per cent of the total abatement potential in France (Mathias et al, 2013)[23]. See figure X below for a complete overview of reduction potentials in States members of the European Union.

Figure IX
Main sources of ammonia emissions



Source: IIASA 2017[24]

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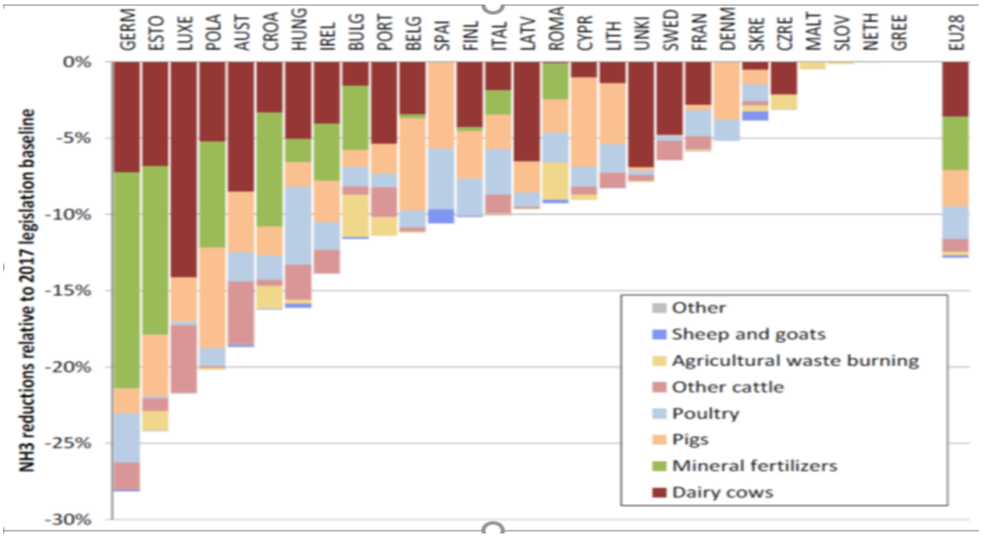
[21] IIASA (2017) Measures to address air pollution from agricultural sources, European commission contract SR11- ENV.C.3/FRA/2013/00131.

[22] Wulf, S., C. Rösemann, B. Eurich-Menden, E. Grimm (2017) Ammoniakemissionen in der Landwirtschaft Minderungsziele und –potenziale Aktuelle rechtliche Rahmenbedingungen für die Tierhaltung, Thünen, Hannover 30.05.2017.

[23] Mathias, E., E. Martin (2013) Analyse du potentiel de 10 actions de réduction des émissions d'ammoniac des élevages Français aux horizons 2020 et 2030, ADEME, Décembre 2013.

[24] IIASA (2017) Progress towards the achievement of the EU's air quality and emissions objectives, International Institute for Applied Systems Analysis, 27 October 2017.

Figure X
Ammonia reductions up to 2030 implied by the European Union National Emissions Ceilings Directive



Source: IIASA 2017

21. The Task Force on Reactive Nitrogen has prepared the Guidance document on integrated sustainable nitrogen management (ECE/EB.AIR/2020/6-ECE/EB.AIR/WG.5 /2020/5), which puts ammonia emission reduction in the broader context of more efficient use of nitrogen in agriculture.[25] An earlier guidance document on preventing and abating ammonia emissions from agricultural sources was adopted by the Executive Body of the Air Convention in 2014 (ECE/EB.AIR/120).[26] The remainder of this section builds upon these documents.

22. Low emission manure application could increase the availability of nitrogen for crop growth - if applied at the right time - and could also reduce the need for mineral fertilizer. Less use of mineral fertilizer would lead to further ammonia reduction, especially if this involves a reduction in the use of urea-fertilizers. If low emission manure application was used to replace the use of mineral fertilizer in agriculture, it would also reduce the total costs of the ammonia emission reduction strategy.

23. Reduction in the total amount of nitrogen that is brought on land, would prevent a shift to water and groundwater pollution and reduce the emission of nitrous oxide.

24. The challenge is to convince farmers that manure is a nutrient resource and a valuable by-product, instead of a waste flow. Drug residues in manure can hinder a “circular agriculture” and might require additional regulation on the use of antibiotics and hormones. To avoid nitrate pollution of groundwater and to obtain the most effective use of manure, the fertilizer value of manure needs to be taken into account, when planning the fertilization of crops. This has long been a requirement in areas of the European Union designated as vulnerable under the Nitrates Directive.[27] On farms or in regions where the production of

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[25] TFRN (2020) draft Guidance document on Integrated Sustainable Nitrogen Management, ECE/EB.AIR/2020/6.

[26] UNECE (2015) United Nations Economic Commission for Europe Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions, https://www.unece.org/index.php?id=41358#:~:text=Theper cent20Ammoniaper cent20Frameworkper cent20Codeper cent20is,Ozoneper cent2Cper cent20andper cent20itsper cent202012per cent20amendment and: Bittman S., Dedina, M., Howard C.M., Oenema, O. and Sutton, M.A. (2014) (eds.) Options for ammonia mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen. TFRN-CLRTAP, http://www.clrtap-tfrn.org/sites/clrtap-tfrn.org/files/documents/AGD_final_file.pdf.

[27] Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC), *Official Journal of the European Communities*, L 375 (1991), pp. 1–8.

manure nutrients exceeds the utilization capacity of the crops, it is necessary to export the excess nutrients to farms or regions where there is unused utilization capacity. When more nutrients are exported than imported, nutrient stocks in soils will be depleted. When more nutrients are imported than exported, nutrients will accumulate in the environment. E.g., in the Netherlands, in 2016, 52 per cent of the nitrogen that was imported via food, feed and mineral fertilizers was exported in the form of agricultural products (meat, dairy and vegetables).[28] The rest (48 per cent) was lost to air, water and soil. This looks bad, but considering that, in 1990, only 30 per cent of the imported nitrogen was exported again, one could also notice a considerable improvement in the efficiency of nitrogen use, due to better use of manure, compost and sewage sludge.

25. Due to economies of scale, the costs of an integrated nitrogen approach are relatively low for modern farms with more the 100 livestock units. According to IIASA, 80 per cent of the manure in Europe is produced by 4 per cent of the farms.[29] One of the implications is that the use of thresholds in relation to farm sizes could be an effective way to address most of the ammonia, while primarily engaging with those farms on which measures would be most cost-effective.[30]

26. However, also for smaller farms, measures are feasible. According to the Guidance Document on Integrated Sustainable Nitrogen Management[31] one of the lowest cost measures is to stimulate grazing on pastures and meadows and substitution of imported cattle feed by cattle feed from the region to better balance imported and exported nitrogen. Incorporating abatement technology in new build is much cheaper than retrofitting. Scrubbing exhaust gasses is only feasible for mechanically ventilated housing (i.e. non-ruminants like pigs and poultry). Slurry acidification can be used in both ruminant (freely ventilated) and non-ruminant housing. This also reduces ammonia emission from storage and field-applied slurry. There is also evidence to suggest that it reduces methane and nitrous oxide emission from slurry stored inside and outside the housing.

27. According to IIASA, technically more ammonia emission reduction is feasible than agreed under the National Emission Ceilings Directive, e.g. up to 50 per cent reduction in Germany.[32] The optimal strategy where additional marginal costs would equal marginal benefits would allow for ammonia reductions of up to almost 40 per cent in Germany and 30 per cent in France (see table 2 below).

28. For most countries, the average costs of ammonia emission abatement would be €0.5–€1.5 per kg ammonia. Such measures include cleaner housing for pigs and poultry, covered manure storage and low-emission manure application. The costs of low-emission manure application vary between €0.2–€4 per kg ammonia, depending on the type of manure, technology and local circumstances.[33]

29. Most of the additional reductions in countries that have already applied low-cost abatement techniques, such as Belgium, Denmark and the Netherlands, would cost in the range of €2.5–€4 per kg ammonia.[34] Measures would include further housing adaptation and deep injection of manure. The use of gas scrubbers for purifying the air from stables currently

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[28] Central Bureau for Statistics, https://www.clo.nl/indicatoren/nl0094-stroomschema-stikstof-en-fosfor.

[29] Amann, M et al, 2017, Measures to address air pollution from agricultural sources, IIASA, https://iiasa.ac.at/web/home/research/researchPrograms/air/policy/SR11-AGRICULTURE-FINAL.pdf.

[30] Annex 1 in TFRN (2011): http://www.unece.org/fileadmin/DAM/env/documents/2010/eb/wg5/wg46/ece.eb.air.wg.5.2010.4.e.pdf.

[31] TFRN (2020) Guidance document on Integrated Sustainable Nitrogen Management, ECE/EB.AIR/2020/6.

[32] IIASA (2017) Progress towards the achievement of the EU's air quality and emissions objectives, International Institute for Applied Systems Analysis, October 27 2017; and: IIASA (2014) The Final Policy Scenarios of the EU Clean Air Policy Package, TSAP Report 11, Version 1.1a, International Institute for Applied Systems Analysis, February 2014.

[33] Reis, S., Howard, C., Sutton, M. A. (2015) Costs of ammonia abatement and the climate co-benefits. Springer Netherlands, Dordrecht.

[34] Wagner, F. et al. (2011) Ammonia reductions and costs implied by three ambition levels, CIAM-report 5/2011.

forms the high end of the cost-curve, with costs up to €15 per kg ammonia.[35] Further investment in and development of such approaches offer the opportunity for upscaling, improving economies of scale and reducing costs, while counting the wider nitrogen benefits as part of an integrated approach.[36] Application of expensive abatement techniques will depend on the remaining profit margins in the agricultural sector (including subsidies). In some regions, a reduction in livestock densities might be more cost-effective to reduce ammonia emissions. This will also be inevitable in countries where animal welfare considerations discourage keeping animals in closed stables.

Table 2

NH_3 emission projections and abatement potential

	NH_3 emission	*reduction percentages*			
	level 2005 in million kg	2020	2030 - NECD	2030 - cost-optimal	2030 - technically feasible
Belgium	74	2	13	16	19
Denmark	73	24	24	37	47
France	675	5	13	29	37
Germany	593	5	29	39	50
Italy	422	5	16	26	29
Netherlands	146	13	21	25	25
United Kingdom	308	8	16	21	22
European Union-28	3982	6	19	27	35

Source: IIASA 2014

30. Additional ammonia emission reduction measures will not only lead to other emission projections for 2030, but also to different estimates for public health damage and damage to ecosystems. Table 3 below shows loss in average life expectancy due to exposure to the total $PM_{2.5}$ concentration. In the countries concerned, approximately half of the $PM_{2.5}$ background concentration is influenced by ammonia emissions. Please note that the variation of the loss in life expectancy among the population is large. Most people will only suffer from minor health effects, while for sensitive people the loss in life expectancy can be several years.

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[35] Even higher costs of air scrubbers are estimated in: Philippe, F.-X.; Cabaraux, J.-F.; Nicks, B. (2011): Ammonia emissions from pig houses. Influencing factors and mitigation techniques. Agriculture, Ecosystems & Environment 141 (3–4) 245–260.

[36] TFRN (2020) Guidance document on Integrated Sustainable Nitrogen Management, ECE/EB.AIR/2020/6.

Table 3
Loss in life expectancy due to $PM_{2.5}$-exposure for various emission projections (in months)

	2005	*2030 - NECD*	*2030 - cost-optimal*	*2030 - technically feasible*
Belgium	10.2	5.9	5.0	4.5
Denmark	6.4	3.5	3.0	2.7
France	8.8	4.4	3.8	3.2
Germany	7.9	4.8	4.0	3.6
Italy	10.2	6.1	4.8	4.3
Netherlands	8.8	5.0	4.3	4.0
United Kingdom	5.8	3.7	2.9	2.6
European Union-28	8.5	5.0	4.1	3.6

Source: IIASA 2014

31. Table 4 below shows the improvement in the protection of ecosystems due to a reduction in nitrogen deposition for various ambition scenarios. In some countries, notably Denmark and the Netherlands, the expected improvement would remain small, even with all technically available measures taken. This is due to the high density of livestock around nature areas in these countries, resulting in further loss in biodiversity. The risk is that characteristic plant species will be overgrown by grass, shrubs and nettle, that will also affect the variety of butterflies and birds. More structural changes would be needed to halt the loss in biodiversity in areas with a high livestock density.

Table 4
Reduction in ecosystem area with excess nitrogen deposition between 2005 and 2030

	2030 - NECD (percentage)	*2030 - Cost-optimal (percentage)*	*2030 – technically feasible (percentage)*
Belgium	92	100	100
Denmark	2	3	7
France	25	43	55
Germany	25	46	55
Italy	44	60	66
Netherlands	5	13	16
United Kingdom	56	80	86
European Union-28	24	35	42

Source: IIASA 2014.
Note: According to national reported data, the share of nitrogen sensitive ecosystems in Belgium is relatively low compared to, for instance, the Netherlands and Denmark. Moreover, farming is concentrated in Flanders (Belgium), while most natural ecosystems are in Wallonia (Belgium).

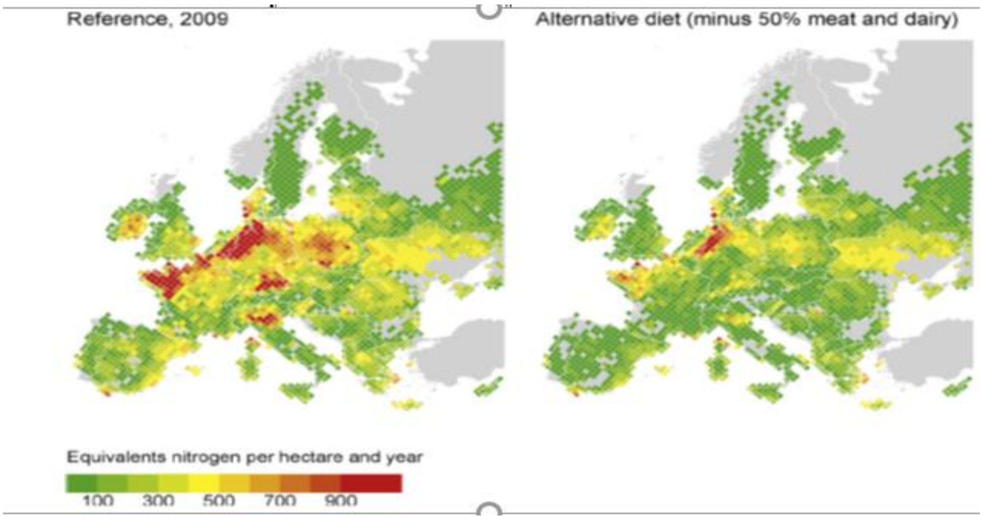
32. One example of such a structural change is to implement a coordinated package of actions to “close” the agricultural nitrogen cycle, i.e. avoid all losses, so that no new inputs of fertilizer nitrogen or biological nitrogen fixation are needed. While such an ambition is

thought not to be feasible, as it is impossible to prevent all denitrification losses in a soil-plant-animal system, there are major opportunities in greatly reducing total nitrogen losses. An important development is the Colombo Declaration on Sustainable Nitrogen Management, which has embraced the ambition to halve nitrogen waste from all sources by 2030 as part of national action plans.[37]

33. At the national scale, a circular agricultural economy with a minimum of losses of nutrients to the environment will require more than only a change in agricultural production techniques. In addition, “demand side” changes will be part of a comprehensive approach. The impact is illustrated in figure XI below. This approach includes reduction of food waste, reduction of overconsumption of calories and a shift towards more sustainable diets, i.e. diets that contribute less to losses of nitrogen. Reducing meat consumption forms a crucial element in such a sustainable diet. Halving meat consumption would reduce ammonia emissions by 43 per cent.[38] That would also significantly reduce emissions of greenhouse gasses and require less land.

34. Another example of a structural change is the production of artificial meat, or using insects or pulses as sources for proteins in the human diet. Moreover, several studies have indicated the health benefits of less overconsumption and eating less red meat.[39]

Figure XI
Annual exceedance of the critical load for N deposition in N per hectare for natural ecosystems, under the reference scenario and the 50 per cent less meat and dairy alternative diet



Source: Westhoek et al. 2015

C. Cost of policy inaction

35. Current agricultural practices lead to a loss of valuable nutrients. If farmers were to adopt an integrated approach to nitrogen and work towards a “circular” agricultural system,

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[37] UNEP (2019): The Colombo Declaration on Sustainable Nitrogen Management. https://papersmart.unon.org/resolution/sustainable-nitrogen-management.

[38] Westhoek, H., et al., 2014, Food choices, health and environment: Effects of cutting Europe’s meat and dairy intake. Global Environ. Change, http://dx.doi.org/10.1016/j.gloenvcha.2014.02.004; and: Westhoek H. et al, (2015) Nitrogen on the Table: The influence of food choices on nitrogen emissions and the European environment (European Nitrogen Assessment Special Report on Nitrogen and Food): http://www.clrtap-tfrn.org/sites/clrtap-tfrn.org/files/documents/EPNFper cent20Documents/Nitrogen_on_the_Table_Report_WEB.pdf.

[39] Van Dooren, C, et al, 2014, Exploring dietary guidelines based on ecological and nutritional values: A comparison of six dietary patterns, Food Policy 44 p36–46, http://dx.doi.org/10.1016/j.foodpol.2013.11.002; Hallström E., et al., 2015, Environmental impact of dietary change: a systematic review, Journal of Cleaner Production 91 (2015) p1-11, http://dx.doi.org/10.1016/j.jclepro.2014.12.008.

less nitrogen would be lost at the farm level and farmers would need to buy less mineral fertilizer. Currently, €15 billion per year is spend in the European Union to buy fertilizers. According to the European Nitrogen Assessment, 50 per cent of the nitrogen fertilizer use is wasted. Halving the use of fertilizers would save $100 billion globally according to the United Nations Environment Programme (UNEP).[40] Moreover, for society as a whole, less nitrogen losses could reduce the damage to public health and ecosystem services and would also reduce the agricultural contribution to climate change, as the production of fertilizers is energy intensive and production and use are also a major source of nitrous oxide (N_2O) emission, a potent greenhouse gas.

36. Current damage in the European Union to ecosystems and human health due to ammonia emissions was monetized by CE-Delft.[41] These external damage costs are not included in food prices. According to CE-Delft, the damage due to ammonia emissions can be valued at €17.50 per kg ammonia (margin: €10–€25.20). These external costs include the contribution of ammonia to environmental damage from acidification and eutrophication, as well as the formation of particulate matter and related loss of live years. Estimates are amongst others based on the HRAPIE methodology of WHO[42] and the valuation of ecosystem damage.[43] An extensive methodological description can be found in de Bruyn et al. (2018).[44] Damage to public health from secondary particulate matter dominates the total damage estimate. Damage to nature includes the additional costs of nature management, such as removal of excess nutrients from nature areas or additional liming to prevent acidification. The damage costs vary across countries and depend, among other things, on population density: in Belgium, Germany and the Netherlands, the damage is estimated at around €30 per kg ammonia, while in Finland, Ireland and Spain, the damage is less than €10 per kg.[45]

37. Studies for specific countries often show lower figures as they do not take into account the impacts on other countries.[46]

38. Using the CE-Delft estimates, the damage due to the remaining European agricultural ammonia emissions in 2030 would amount to almost €60 billion per year (€35 billion to €85 billion).[47] This is 15 per cent of the total agricultural output and more than 50 per cent of the annual income (net value added) from agricultural activity in the European Union.[48] Note

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[40] UNEP Frontiers Report: The Nitrogen Fix: https://apo.org.au/sites/default/files/resource-files/2019-03/apo-nid224376.pdf. See also.

[41] de Bruyn et al. (2018) Environmental Prices Handbook EU28 version - Methods and numbers for valuation of environmental impacts, CE-Delft.

[42] WHO (2013) Health risks of air pollution in Europe – HRAPIE project Recommendations for concentration–response functions for cost–benefit analysis of particulate matter, ozone and nitrogen dioxide.

[43] Holland M, R Maas (2014) Quantification of economic damage to biodiversity, ECLAIRE Project, Deliverable 18.3.

[44] See also: CE-Delft (2019) Handbook on the external costs of transport - Version 2019.

[45] For Germany €32 per kg is estimated in Matthey A and B. Bünger (2018) Methodological Convention 3.0 for the Assessment of Environmental Costs, Umwelt Bundes Amt.

[46] For Denmark €20 per kg was estimated in: Mikael Skou Andersen, Lise Marie Frohn Rasmussen og Jørgen Brandt (2019) Miljøøkonomiske beregningspriser for emissioner 3.0, Aarhus Universitet; for the UK €6,80 per kg was estimated with a broad margin (€1,25 - 21): Ricardo (2019) Air Quality damage cost update 2019, Report for Defra AQ0650: for Finland the estimate was €1,20 (0,70 – 2,80): Kukkonen, et al. (2019) Modelling of the public health costs of fine particulate matter and results for Finland in 2015, ACP, https://doi.org/10.5194/acp-2019-702 and for Ireland: €0,82: EnvEcon (2015) Marginal Damage Cost Estimates for Air Pollutants in Ireland.

[47] This estimate is lower than €70-320 billion that was estimated in the European Nitrogen Assessment, but that figure also includes the impacts of nitrate and the climate impacts of nitrous oxide (ENA Technical Summary page xiviii) Also see: Brunekreef B., Harrison R.M., Künzli N., Querol X., Sutton M.A., Heederik D.J.J. and Sigsgaard T. (2015) Reducing the health effect of particles from agriculture. *Lancet Respiratory Medicine* (8 October 2015), http://dx.doi.org/10.1016/S2213-2600(15)00413-0.

[48] Total agricultural output in the European Union in the past decade was around €400 billion (of which around 40 per cent animal). With input costs of €230 billion and depreciation costs of €55 billion, the net annual value added (income) is €115 billion, excluding taxes and subsidies. Net subsidies are around €40 billion (35 per cent of the net value added).

that the agricultural sector in Europe also receives a net subsidy of around 35 per cent of the net value added, among other things, to keep food prices low.

39. By definition, €60 billion is the (gross) societal costs of taking no additional policy actions. With an emission reduction of 30–50 per cent, the damage could be avoided. For agriculture, abatement costs can be estimated at €0.7 billion –€5.7 billion per year, depending on the policy ambition level (IIASA, TSAP-report #11, 2014). To reach a 30–50 per cent reduction, in some regions additional non-technical measures would be required.

40. The damage cost estimate of €17.50 per kg ammonia is higher than the abatement cost estimates. According to a German study (Wulf et al, 2017), the average costs of ammonia abatement would be €0 to €4 per kg. The high-end estimate of the most expensive reduction measure (air scrubbers on stables) would, according to this study, cost up to €15 per kg.

41. Including the damage costs in the prices of food would lead to a price increase of meat and dairy products. According to CE-Delft[49] a true price of beef and pork that includes the environmental damage from nitrogen losses, would have to be 25–35 per cent higher. Raising the prices of meat and dairy products would lead to an increase in the costs of meals, which would require measures to ensure the adequate nutrition of low-income groups. However, an increase in the costs of meals could be limited, if higher meat and dairy prices were combined with campaigns aimed at dietary change.

III. Ammonia in Canada and the United States of America

42. Emissions of most air pollutants have been on the decline in Canada and the United States of America, leading to improved air quality in many regions. However, nearly one quarter of Canadians still live in areas that exceed one or more ambient air quality standards and 10 per cent of the population of the United States of America lives in areas that exceed ambient air quality standards for fine particulate matter ($PM_{2.5}$).[50] Emissions of ammonia are of concern in Canada and the United States of America as atmospheric ammonia is a key precursor to the formation of fine particulate matter ($PM_{2.5}$) and contributes to acid deposition and eutrophication. The health effects of atmospheric particulate matter are numerous, including heart and lung disease, stroke, asthma, diabetes, as well as neurodegenerative diseases such as dementia. Atmospheric ammonia also plays an important role in nitrogen cycling and on ecosystem health, however, an exceedance in critical loads of nitrogen can lead to adverse environmental effects. These have widespread impacts on the environment, as they affect terrestrial and aquatic biodiversity and sustainability. Atmospheric PM also contributes to decreased visibility. Canada and the United States of America have a long history of cooperation on monitoring and assessment of acid deposition,[51] including under the 1991 Canada-United States Air Quality Agreement.

43. While much progress has been made in the last two decades in reductions of other precursors to $PM_{2.5}$ such as NO_x and SO_2, emissions, and correspondingly atmospheric concentrations, of ammonia have continued to rise in both Canada and the United States of America. In both countries, the agricultural sector is the dominant source of ammonia, accounting for 93 per cent of national emissions (Canadian Air Pollutant Emissions Inventory, 2020; United States Environmental Protection Agency National Emission Inventory, 2020). Areas of intense agricultural activity include southern Ontario and Quebec, southern British Columbia, Alberta, Saskatchewan, as well as the Midwestern United States of America, California and North Carolina. Ammonia emissions near the Canada-United States of America border also have transboundary impacts on air quality (see figure XII below). More detailed assessments are needed to quantify the impacts.

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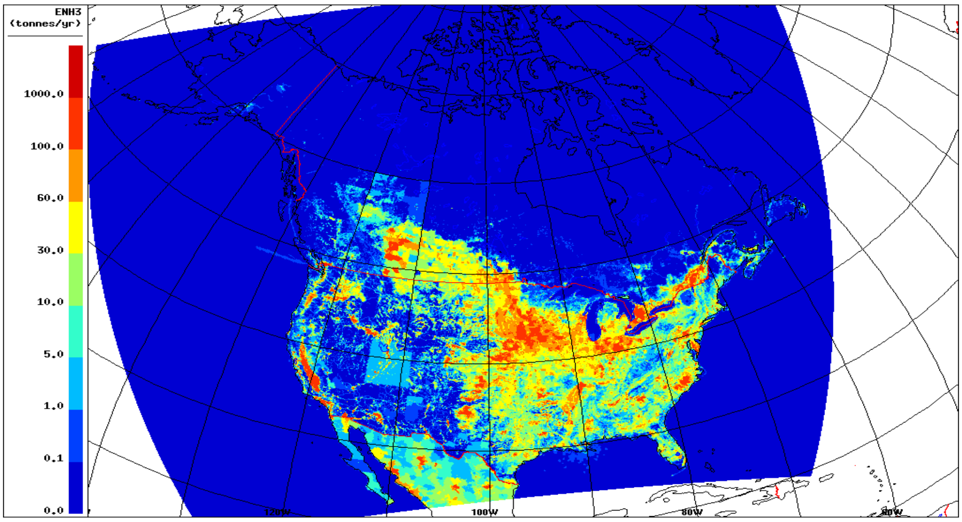
[49] CE-Delft, The true price of meat, 2018.

[50] https://www3.epa.gov/airquality/greenbook/popexp.html.

[51] http://pubs.awma.org/flip/EM-June-2019/schwede.pdf.

Figure XII

Annual North American ammonia emissions (tonnes/grid cell).



Source: based on 2013 Canadian and 2017 projected U.S. inventories, 10 km x 10 km GEM-MACH grid

A. Ammonia emission trends

44. In Canada, ammonia emissions increased by 21 per cent over the period 1990–2018, mainly due to increased agricultural use of nitrogen-based fertilizers. Ammonia emissions in Canada are dominated by animal production, which made up 59 per cent of emissions in 2018 and crop production, accounting for 35 per cent. All other sources of ammonia emissions combined accounted for only 7 per cent of emissions in 2018. Other sources include manufacturing, incineration and waste, and transportation and mobile equipment.

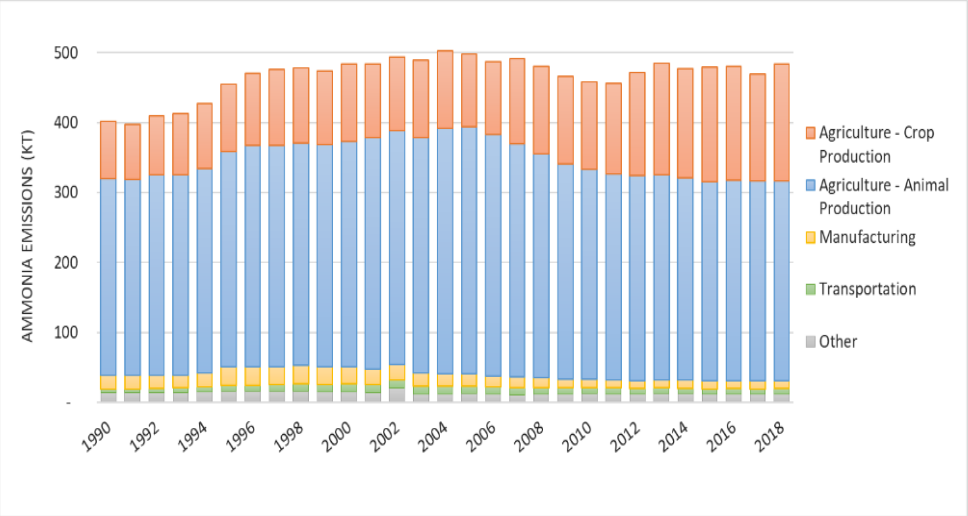
45. Two distinct trends are observed in Canadian national ammonia emissions (see figure XIII below). The first trend is a consistent rise in emissions from crop production, which more than doubled between 1990 and 2018, and have been increasing at a greater rate since 2005, as a result of a rise in the application of nitrogen-based fertilizers for annual crop production.

46. The second trend pertains to emissions from animal production, which, after consistently increasing from 1990 levels, peaked in 2006, and have decreased thereafter. For comparison, emissions from animal production made up 71 per cent of total Canadian ammonia emissions in 2005. In 2018, they made up 59 per cent. The decline in demand for beef and continuing impacts of the 2003 bovine spongiform encephalopathy crisis have resulted in a decrease in the number of beef cattle produced on an annual basis, and therefore have led to a drop in emissions.

47. These two counter-acting trends in the past decade have resulted in modest fluctuations in overall Canadian national ammonia emissions. While Canadian emissions have increased 21 per cent since 1990, they have largely plateaued since 2005. Emissions increases at the national level are mainly being driven by rising agricultural production in the western provinces. According to current projections, Canadian ammonia emissions overall will increase over the coming decade due to continued increase in nitrogen-based fertilizer application for crop production.

Figure XIII

Estimated annual ammonia emissions for Canada (national total)



48. In the United States of America in 2017, approximately 59 per cent of ammonia emissions is attributed to agricultural livestock. The next largest categories are fertilizer application (21 per cent) and agriculture fires and prescribed burning (5 per cent). A combination of other emission source categories, including fuel combustion, industrial processes, and waste management, contribute the remaining 15 per cent of the total.[52]

B. Ambient concentrations and deposition

49. While ammonia readily deposits and can be re-emitted into the atmosphere, generally causing negative impacts locally, ammonium aerosols are transported and deposited over long distances. Globally, North America is an intensive atmospheric ammonia emission zone.[53] Although decreased ammonia emissions have been reported in some provinces and States across Canada and the United States of America, increasing trends in emissions at the national level and in ammonia concentrations have been identified from satellite observations and ground-level measurements.[54][55]

50. The National Atmospheric Deposition Programme (NADP) (including the National Trends Network (NTN)), the Atmospheric Integrated Research Monitoring Network (AIRMoN), the Clean Air Status and Trends Network (CASTNET) and the Canadian Air and Precipitation Monitoring Network (CAPMoN) are the primary networks supporting nitrogen deposition assessments in Canada and the United States of America. Other air monitoring networks measuring atmospheric nitrogen include the Ammonia Monitoring Network (AMoN) under NADP, the Interagency Monitoring of Protected Visual Environments (IMPROVE), the Canadian National Air Pollution Surveillance (NAPS) Programme and several other networks that collectively feed data into the air quality system of each respective country. There is a need to measure both the gaseous form (NH_3) and particle form (NH_4^+)

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[52] US EPA (2017) National Emission Inventory. Data available at ftp://newftp.epa.gov/air/nei/2017/tier_summaries/.

[53] Xiaohong Yao and Leiming Zhang (2019) Causes of Large Increases in Atmospheric Ammonia in the Last Decade across North America. *ACS Omega*. 2019 Dec 24; 4(26): 22133–22142. https://pubs.acs.org/doi/abs/10.1021/acsomega.9b03284.

[54] J. X. Warner, R.R. Dickerson, Z. Wei, L.L. Strow, Y. Wang, and Q. Liang (2017) Increased atmospheric ammonia over the world's major agricultural areas detected from space. *Geophys. Res. Lett.*, March 2017, (44) 2875-2884: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016GL072305.

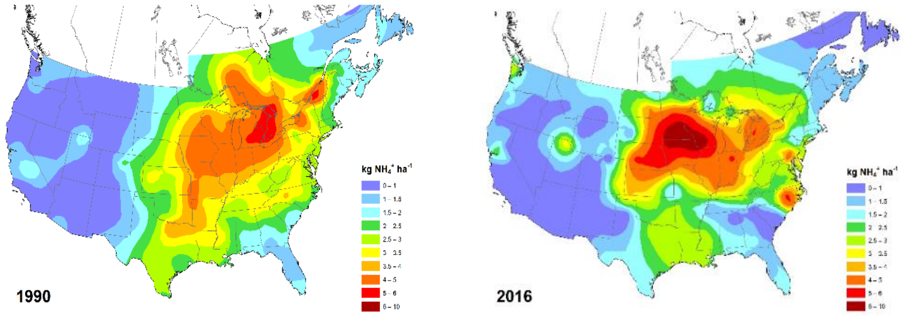
[55] Yu, F., Nair A. A., & Luo, G. (2018) Long-term trend of gaseous ammonia over the United States: Modeling and comparison with observations. *Journal of Geophysical Research: Atmospheres*, August 2018, (123) 8315–8325: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018JD028412.

of reduced nitrogen to reduce the overall uncertainty in the chemical formation of $PM_{2.5}$ and transport and deposition of reduced nitrogen compounds.

51. Increasing trends in annual ambient ammonia concentrations were observed at NADP/AMoN sites across Canada and the United States of America, with the percentage increases exceeding 40 per cent in the last 8–13 years.[56] Established in 2007, NADP/AMoN is the only network providing a consistent, long-term record of ambient ammonia concentrations across the United States of America and at some sites in Canada. These ground-based measurements have been used to validate satellite observations showing similar trends with improved spatial coverage. Observed increases in ambient NH_3 are greater than can be explained by emissions changes alone. The increases in ambient NH_3 concentrations can be explained by a combination of factors: increased emissions in some regions; lower ambient levels of sulfate and nitrate converting ammonia to ammonium; and changes in meteorological conditions.

52. Deposition of reactive nitrogen is highest in central and eastern Canada and the central United States of America. The main sources of nitrogen deposition are nitrogen oxides in and around urban areas and reduced nitrogen in agricultural regions. In Canada, concentrations of particulate ammonium nitrates and ammonium sulfates are declining due to reduction of precursor emissions (sulfur and nitrogen oxides). However, while wet deposition of sulfate and nitrate have also declined, wet deposition of ammonium has not changed significantly since 1990 (see figure XIV below). Further work is required to assess how particulate ammonium interacts with other pollutants. In the United States of America, wet deposition of oxidized nitrogen has declined in nearly all States, but from 1990 to 2010, ammonium wet deposition increased in 37 of the 45 States where monitoring is available.[57]

Figure XIV
Observed annual wet deposition of ammonium in 1990 (left) and 2016 showing areas between Canada and the United States of America where transboundary ammonia emissions may require further assessment.



Source: Interpolated surface based on data from United States National Atmospheric Deposition Programme National Trends Network and Canadian Air and Precipitation Monitoring Network

C. Abatement measures

53. Ammonia continues to be a major contributor to secondary $PM_{2.5}$ particularly in eastern Canada and the central United States of America, through the reaction of NH_3 with oxides of sulfur and nitrogen (SO_x and NO_x) to form ammonium sulfate and ammonium nitrate. As a result, during high pollution events, ammonium can, in some regions, account for up to 25 per cent of the $PM_{2.5}$ mass. With the reported and observed increases in Canadian

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[56] T.J. Butler, F. Vermeylen, C.M. Lehmann, G.E. Likens, M. Puchalski (2016) Increasing ammonia concentration trends in large regions of the USA derived from the NADP/AMoN network. *Atmospheric Environment* December 2016, 146 132-140; DOI: 10.1016/j.atmosenv.2016.06.033.

[57] Y. Li, B. A. Schichtel, J. T. Walker, D. B. Schwede, X. Chen, C. M. B. Lehmann, M. A. Puchalski, D. A. Gay, J. L. Collett (2016) The importance of reduced nitrogen deposition. *Proceedings of the National Academy of Sciences* May 2016, 113 (21) 5874-5879; DOI: 10.1073/pnas.1525736113.

and United States of America ammonia emissions, some of the expected benefits of the significant reductions of these strong acidic precursors are being offset. This is largely due to the fact that atmospheric ammonia is highly reactive, and will not remain in gaseous form long before either reacting with acidic gases, or undergoing dry or wet deposition. However, recent measurements and modeling have shown that the sensitivity of $PM_{2.5}$ to ammonia varies significantly by region, according to the presence of precursors (Franchin et al., 2018).[58]

54. In Canada, gaseous ammonia is on the list of Schedule 1 toxics substances under the Canadian Environmental Protection Act, 1999, because it has been identified as one of the principal precursors to fine particulate matter, and is thus a contributor to poor air quality leading to adverse health impacts. Domestically, Canada has a number of nationwide guidelines on agricultural practices, however these focus on achieving environmental standards such as safe nitrate concentration in drinking water, rather than requiring emission reductions. Recognizing the environmental as well as practical and economic benefits from improved nitrogen use efficiency, the agricultural sector in Canada has been proactive in this regard, and has moved towards improved nitrogen use efficiency over the years (including several practices accepted as mitigation methods by the United Nations Economic Commission for Europe (ECE))[59] due primarily to practical or economic reasons.

55. In October 2018, Environment and Climate Change Canada held an ammonia workshop that brought together scientists and policy makers from Canada, the United States of America and Europe to discuss the importance of ammonia, as well as the state of atmospheric ammonia policy, science and mitigation. The workshop concluded with a number of key messages regarding the health and environmental impacts of ammonia, as well as tools and approaches available for mitigation. Discussions in Canada to assess appropriate policy tools and measures that can reduce emissions of atmospheric ammonia and increase awareness of these issues are ongoing

IV. Ammonia in Eastern Europe, the Caucasus and Central Asia

A. Emissions and deposition

56 The nitrogen deposition in Eastern Europe. Caucasus and Central Asia shows large variations (see figure XV below). In large parts, the deposition is low compared to Central and Western Europe. However, emissions of ammonia tend to increase.[60] In areas with many small-scale farms, nitrogen losses are often the result of inefficient use of nutrients. When livestock densities in such areas are high, the accumulated emissions from small farms can cause eutrophication problems.

57. In large parts of the Russian Federation, Ukraine and Belarus, critical loads for nitrogen are exceeded. In the Russian Federation (European part only), 40–50 per cent of the ecosystems are at risk. In Belarus and Ukraine this is almost 100 per cent.[61] Available air quality data indicate a substantial higher exposure to particulate matter. More measurements and modelling would be required to assess the contribution of secondary particles (formed by ammonia) to the exposure in densely populated areas.

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[58] Franchin, A. et al. (2018) Airborne and ground-based observations of ammonium-nitrate dominated aerosols in a shallow boundary layer during intense winter pollution episodes in northern Utah, Atmos. Chem. Phys., 18, 17259–17276, 2018, https://doi.org/10.5194/acp-18-17259-2018.

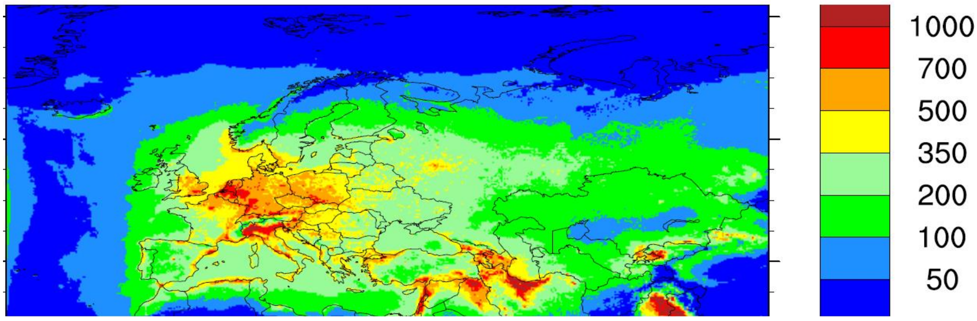
[59] S. Bittman, S. C. Sheppard, D. Hunt. (2017) Potential for mitigating atmospheric ammonia in Canada. Soil Use and Management, June 2017, 33, 263–275.

[60] CEIP, https://www.ceip.at/webdab-emission-database.

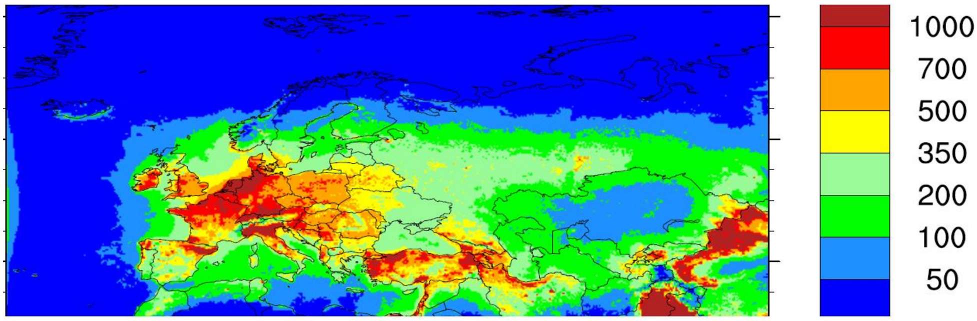
[61] Hettelingh J-P, M. Posch, J Slootweg (eds) (2017) European critical loads: database, biodiversity and ecosystems at risk, CCE Final Report 2017, Coordination Centre for Effects, RIVM Report 2017-0155, Bilthoven, Netherlands.

Figure XV

Deposition of oxidized and reduced nitrogen in 2018 over the whole EMEP-region (in kg N per km^2)



(b) oxidized N



(c) Reduced N

Source: EMEP Meteorological Synthesizing Centre-West

B. Abatement measures

58. Ammonia policies in countries of Eastern Europe, the Caucasus and Central Asia are described in van der Hoek and Kozlova.[62] Emissions dropped sharply in the early 1990s due to the reduction in the number of animals that followed after the political and economic transition; since 1995 emissions have been rising slowly. In the Russian Federation (European part only), the available nitrogen in manure (organic fertilizer) was reduced by more than 85 per cent and agricultural ammonia emissions from husbandry in the Russian Federation (European part only) were reduced by 60 per cent.[63] The same developments were observed in Kazakhstan: after a sharp decline in cattle numbers between 1993 and 1998, the numbers show a slow annual increase.[64]

59. The reduction in ammonia emissions showed no decrease in ammonia concentrations. Modelling suggested that this was due to the simultaneous decline in SO_2 and NO_x emissions: less ammonia was used for the formation of ammonium-nitrate and ammonium-sulfate.[65]

60. Cattle densities in Eastern Europe, Central Asia and the Caucasus are lower than in Western Europe. Compared to the Russian Federation (European part only) and Central Asia,

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[62] Van der Hoek, K.W. and N.P. Kozlova (eds) (2014) Ammonia workshop 2012 Saint Petersburg. Abating ammonia emissions in the UNECE and EECCA region. Семинар по аммиаку 2012, Санкт Петербург. Снижение выбросов аммиака в регионах ЕЭК ООН и ВЕКЦА. RIVM Report 680181001/SZNIIMESH Report. Bilthoven, The Netherlands. ISBN: 978-90-6960-271-4.

[63] Morozova, I.A., N.M. Golovina, Y.S. Ignatyeva (2014) National registration of nitrogen emissions in the Russian Federation, in: Van der Hoek, K.W. and N.P. Kozlova, Eds.

[64] Eserkepova, L.B., L.V. Lebed, Z.R. Tokpajev (2014) Reactive nitrogen emissions in the Republic of Kazakhstan, in: Van der Hoek, K.W. and N.P. Kozlova, Eds.

[65] Horvath et al. (2009) Long-Term Record (1981–2005) of ammonia and ammonium concentrations at K-Puszta Hungary and the effect of sulfur dioxide emission change on measured and modelled concentrations. Chapter 12, in: *Atmospheric Ammonia: Detecting emission changes and environmental impacts* (eds. M.A. Sutton, S. Reis and S.M.H. Baker), pp 181-186, Springer.

cattle densities in Belarus and the Caucasus are relatively high. The past decades show a gradual increase in animal numbers. Currently, the main driver for ammonia policy is the need for a more efficient use of nitrogen. In the Russian Federation (European part only), around 80 per cent of the nitrogen input to agricultural land currently comes from mineral fertilizers.[66]

61. Estimates for Belarus showed that, with technically feasible measures (e.g. covered manure storage and immediate incorporation of manure on land), ammonia emissions from husbandry could be reduced by around 20 per cent. But the costs seem still to be prohibitive for farmers. Implementation is stimulated via pilot projects.[67]

V. Conclusions and recommendations

62. Ammonia emissions, concentrations and deposition in Europe show a moderate decline over the last 15 years compared to sulfur dioxide and nitrogen oxides. Ammonia emissions in North America and countries in Eastern Europe, the Caucasus and Central Asia tend to increase. The damage of ammonia emissions to public health and ecosystems can be valued at €10–€25 per kg ammonia. Substantial reductions of ammonia emissions, even beyond the current obligations in the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone and the revised European Union National Emission Ceilings Directive, are still possible. Abatement costs of ammonia are significantly lower than the damage per kg, and vary from €0 to €4 per kg ammonia for most countries, up to €15 per kg ammonia in some areas with a high density of livestock.

63. Cost-effective measures to further reduce ammonia emissions differ among various parts of Europe and North America. Covering of manure storage and optimal application of manure for crop growth are simple and cheap measures. The limitation of the use of urea fertilizer, or a further substitution of mineral fertilizers by manure is a relatively low-cost strategy in areas with sufficient livestock. It would, however, require records to be kept of manure transports in order to avoid conflicts with nitrate leaching.

64. Low-emission manure application (injection on grassland and direct incorporation on arable land) is the most effective measure, but it requires investments in machines that will pay back if the measure is be combined with less mineral fertilizer use.[68] Low-emission manure application is currently the most effective abatement option, e.g. for Germany and France, to reduce ammonia emissions.

65 Areas with high livestock densities (Belgium, Denmark and the Netherlands), have already taken these low-cost measures, in order to protect ecosystems. Further extension of the use of air scrubbers for stables would – although expensive – be a technical option in areas with a high density of livestock to increase the protection of public health and of nature areas. Further investment, innovation and upscaling of such approaches is expected to further reduce prices, while contributing to the development of the nitrogen circular economy.

66. Further emission reduction of ammonia would require structural changes, including increasing the nitrogen use efficiency. Such an approach would require substitution of mineral fertilizers by the use of manure (“organic” fertilizer) and production of other sources of protein than meat. Also, demand side changes would be needed, such as a reduction of food waste, overconsumption and dietary changes.

67. Linkages with water protection (e.g. nitrate leaching) and climate policies require attention in order to avoid negative side effects from ammonia abatement measures and to profit from potential synergies. E.g. for cattle, changes in feed might become an option to reduce ammonia emissions, but such a strategy would have to be combined with the aim to

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[66] *Lukin, S.M., K.S. Nikolskiy*, V.V. Ryabkov, I.V. Rusakova (2014) Methods to reduce ammonia nitrogen losses during production and application of organic fertilizers, in: Van der Hoek, K.W. and N.P. Kozlova, Eds.

[67] Kakareka, S.V. , A.V. Malchikhina (2014) Scenarios for reduction of ammonia emissions in Belarus, in: Van der Hoek, K.W. and N.P. Kozlova, Eds.

[68] Haan, BJ de, et al. (2009) Emissiearm bemesten geëvalueerd, PBL-report 500155001, Bilthoven.

also reduce methane emissions. Less use of mineral fertilizers (e.g. increasing the nitrogen use efficiency by precision farming) would have benefits for both air quality and climate as, for the production of mineral fertilizer, large amounts of natural gas are needed, while the use and production of mineral fertilizers contribute to emissions of nitrous oxide.

68. An increased use of energy crops in the transition towards a carbon neutral economy, would mean that we need to reduce the land occupied by other crops while maintaining food security. That means in practice reducing the land used to grow crops to feed animals. Increasing nitrogen use efficiency will help, but is unlikely to be sufficient alone, so animal production would likely to have to fall.

69. Because of the transboundary role of ammonia in the formation of secondary particulate matter, biodiversity protection, and the linkages with climate and food security policies, it is important to continue the exchange of information on technical and non-technical abatement policies. At least in the short run, clarity in the timing of envisaged ammonia abatement measures would help neighbouring countries to underpin their national air quality plans with quantitative estimates.