Assessment Report on Ammonia – 2020

draft November 2020

Content

This report is written at the request of the Executive Body of the Convention on Long-Range Transboundary Air Pollution as part of the work plan of the Convention as a general introduction for policy makers to ammonia related issues. The Task Force on Integrated Assessment Modelling was asked to coordinate the work and cooperate with experts from the Task Force on Measurement and Modelling and the Task Force on Reactive Nitrogen.

The report brings together key data and research findings from various studies. Its goal is to give a concise and policy oriented overview. The focus of this report is on ammonia. Both ammonia and nitrogen oxide emissions contribute to eutrophication and acidification, as well as the formation of secondary particulate matter. In the past decades, policy efforts have been more focused on emission reduction of nitrogen oxides than on ammonia emission reduction. This report aims to give arguments to put more emphasis on ammonia.

The report is mainly based on experiences in Europe. Ammonia issues in North America and in Eastern Europe, Central Asia and Caucasus are presented in the annexes.

1. Summary

Ammonia emissions have reduced much less in the past decades compared with other pollutants such as sulphur 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 PM2.5. In and around regions with high livestock densities, ammonia is responsible for more than 50% of the nitrogen deposition and PM2.5 exposure. Without additional policy action, the associated monetary damage in the EU can be estimated at 6o billion euro per year from 2030 onwards. This damage is not included in the production costs or the prices of meat and dairy. Estimates show that their current market prices would have to raise by 25-35% to cover the environmental damage.

In order to avoid damage to ecosystems and health a 30-50% reduction in ammonia emissions is required in UNECE countries 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% reduction), but in some regions (where the most cost effective measures have already been implemented) a reduction of livestock densities can be inevitable, if legally protected natural habitats are to be safeguarded for the future.

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 save 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 - with the current profit margins of farmers - 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.

2. Current status and trends

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 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.

In areas with high densities of livestock, emissions per hectare are 3-5 times higher than on average in Europe (figure 1a). 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] The emissions from fertilizers are smaller in Europe because ammonium nitrate based fertilizers predominate, although use of urea fertilizers has been increasing. A small part (around 10%) of the annual ammonia emissions comes from industry, households and traffic.

In Europe, ammonia (reduced nitrogen) is the dominant cause of nitrogen deposition on nature areas, which. This is even the case in areas with high densities of traffic and emissions of nitrogen oxides (figure 1b). However, in the eastern part of North America, nitrogen oxides are the dominant cause of nitrogen deposition.[2]

Excessive nitrogen deposition can contribute to the loss of plant species, butterflies and birds (figure 1c)[3]. The higher the spatial resolution of ecosystem maps, the more sensitive nature areas 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 the Baltic sea.

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[4]. In large areas of Europe, more than half of the anthropogenic particulate matter concentrations is not emitted directly, but is formed in the air when ammonia reacts with nitrogen oxides or sulphur dioxide (the so-called secondary particles) (Figure 1d). Also, in North America and Asia the role of ammonia in the formation of particulate matter is getting more attention[5].

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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] Kanakidou, et al. (2016) Past, Present and Future Atmospheric Nitrogen Deposition, Journal of the Atmospheric Sciences, vol73 pp 2039-2047

[3] 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).

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

[5] 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.

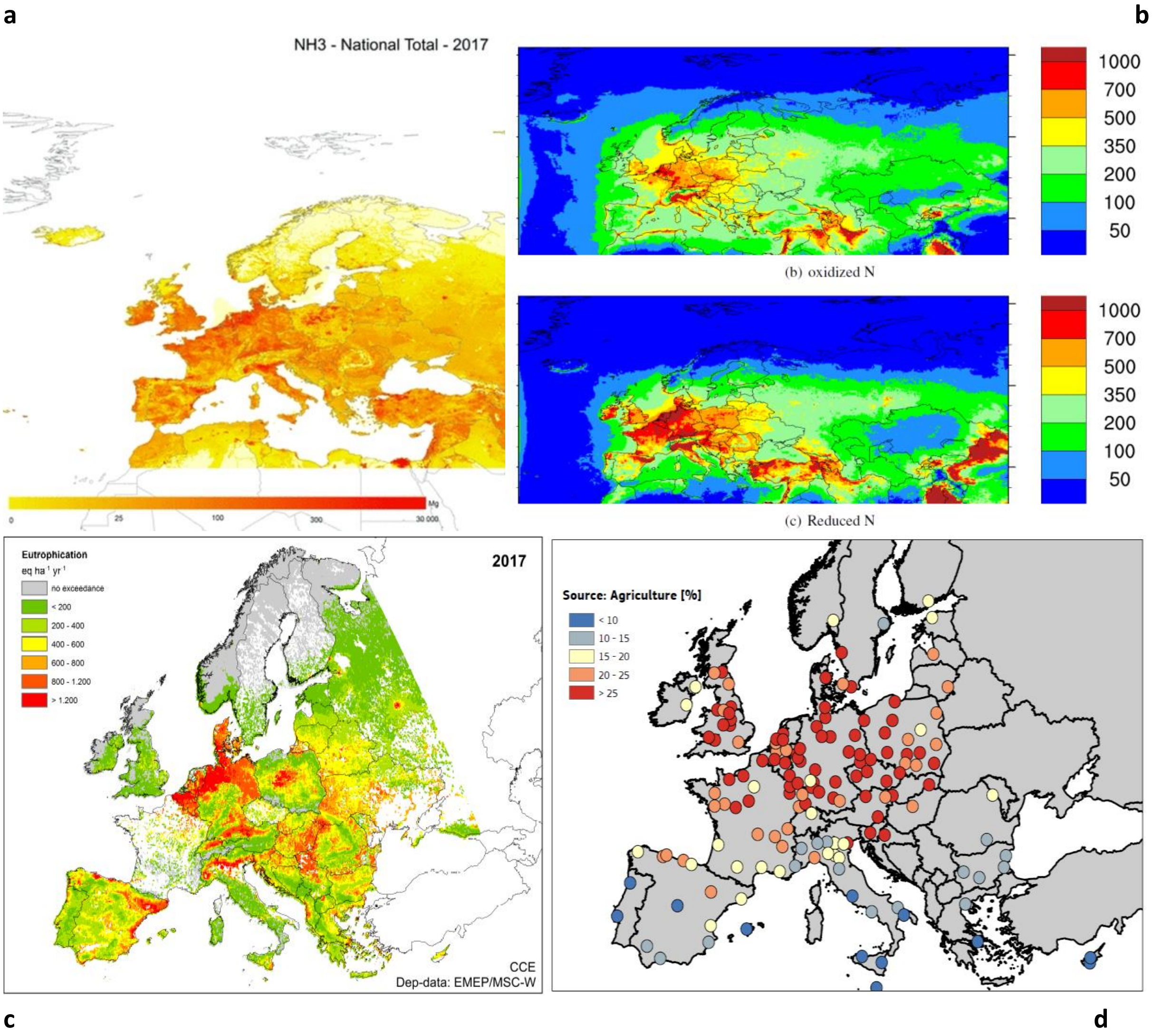

Figure 1: (a) Ammonia emissions in kg NH_3 per km2 (EMEP-CEIP), (b) Nitrogen deposition per grid from oxidised nitrogen (top) and reduced nitrogen (bottom) in 2018 in kg N per km^2 (EMEP-MSCW)[6], (c) Exceedance of the critical load for nitrogen in 2017 (CCE)[7] and (d) share of ammonia related secondary aerosols in urban PM2.5-concentrations in 2015 (JRC) [8]

Figure 2a shows the origin of the particulate matter concentrations in 2009 in cities (measured as PM2.5 - particulate matter with a diameter of less than 2.5 micrometer). The light green and dark green bars show the secondary particles (ammonium nitrates and ammonium sulphates respectively) that are both influenced by ammonia emissions. See also the source apportionment in Brussels, where according to Sherpa-model of JRC, the largest single source-sector contribution to PM2.5 is agriculture, i.e. ammonia emissions (figure 2b). The pink line in the figure 2a indicates the air quality guideline level of 10 micrograms per cubic meter of the World Health Organisation.[9] In Benelux-countries and surrounding parts of Germany and France more than 50% of the average PM2.5

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[6] EMEP (2020) Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components, Status report 1/2020

[7] Hettelingh, JP, et al. (2015) Effects-based integrated assessment modelling for the support of European air pollution abatement policies. In: W. de Vries, J-P. Hettelingh & M. Posch (Eds), Critical Loads and Dynamic Risk Assessments: Nitrogen, Acidity and Metals in Terrestrial and Aquatic Ecosystems, Springer, pp. 613-635

[8] Thunis et al. (2018) PM2.5 source allocation in European cities: A SHERPA modelling study, Atmospheric Environment vol 187 pp 93-106

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

concentration consists of secondary particles. According to EMEP modelling foreign sources contribute 70-80% to the secondary PM2.5 concentrations in Benelux countries.

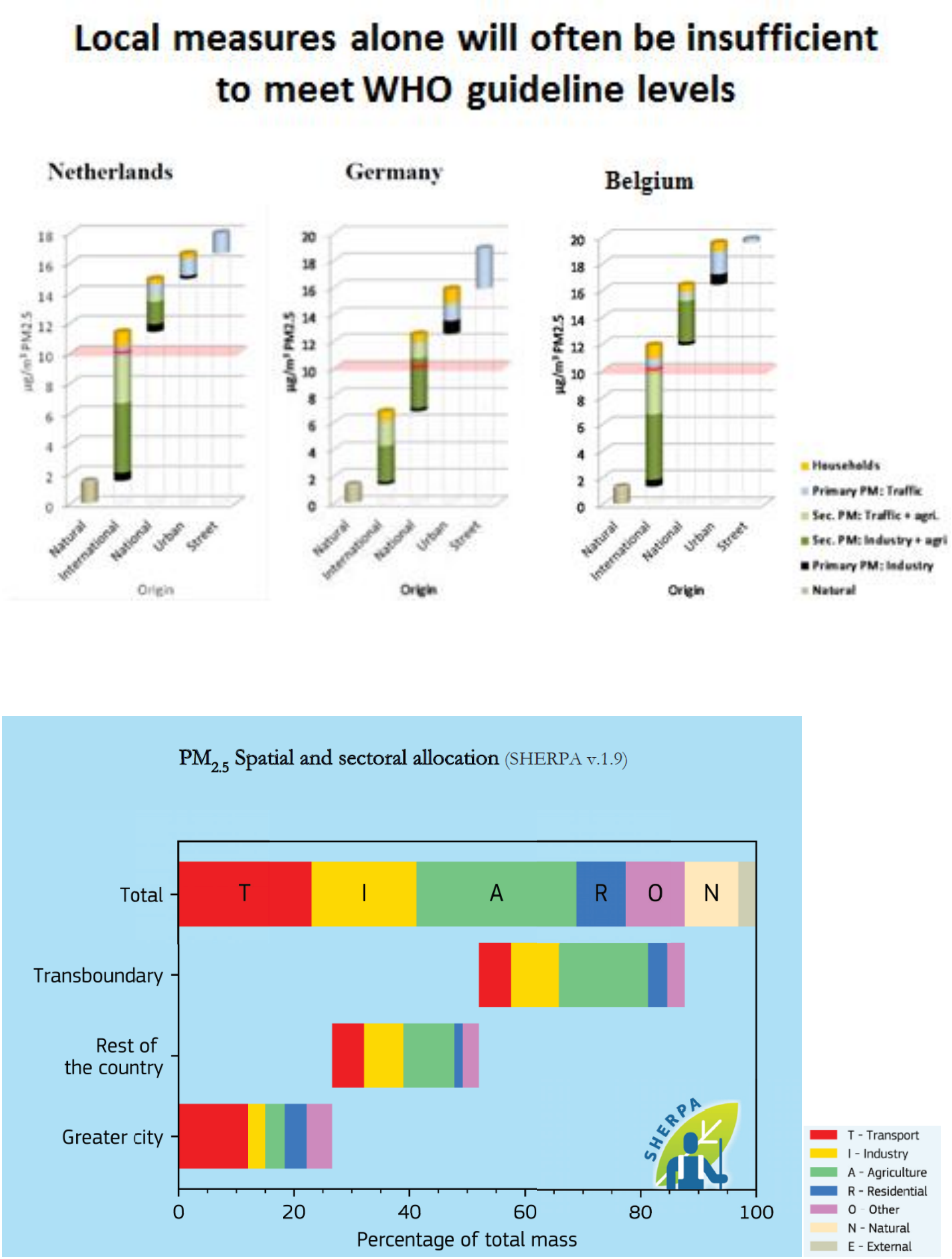

Figure 2: (a) Origin of urban background concentrations of PM in the Netherlands, Germany and Belgium according to the GAINS-model (IIASA) [10] *and (b) in Brussels according to the Sherpa-model (JRC, 2017)*[11]

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[10] IIASA (2014) Urban PM2.5 levels under the EU Clean Air Policy Package, TSAP Report 12, International Institute for Applied Systems Analysis, October 2014

[11] JRC (2017) Urban PM2.5 Atlas of air quality in European cities, European Commission. The Sherpa tool is a screening model based on more detailed chemistry transport modelling on a scale of around 7km. Its applicability to simulate urban concentration levels and estimate the source apportionment for urban areas is being discussed within the Forum of Air quality Modelling in Europe (FAIRMODE). The contribution of traffic will be higher along roads with busy traffic.

Currently, exceedances of the EU Air Quality Limit Value of particulate matter occur frequently in cities during weeks with dry weather and high ammonia emissions, e.g. in early spring when manure that was stored during the winter is applied on agricultural land.[12]

Since 2000, only modest reductions of ammonia emissions were achieved in Europe and north America compared to the reductions of other pollutants like sulphur dioxide, nitrogen oxides and primary particulate matter (see figure 4a). According to the EMEP-Trend report observations of ammonium concentrations at EMEP-background stations showed no significant downward trend for Europe as a whole after 2000 (see figure 4b)[13], although a significant reduction in particulate matter ammonium concentrations has been observed regionally (e.g. 48% reduction for UK between 1999 and 2014).[14] 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.[15]

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[12] 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

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

[14] 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/

[15] 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. http://www.ammonia-ws.ceh.ac.uk/documents/BGD_NHx%20trends%20Bleeker_new%20version.pdf 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.

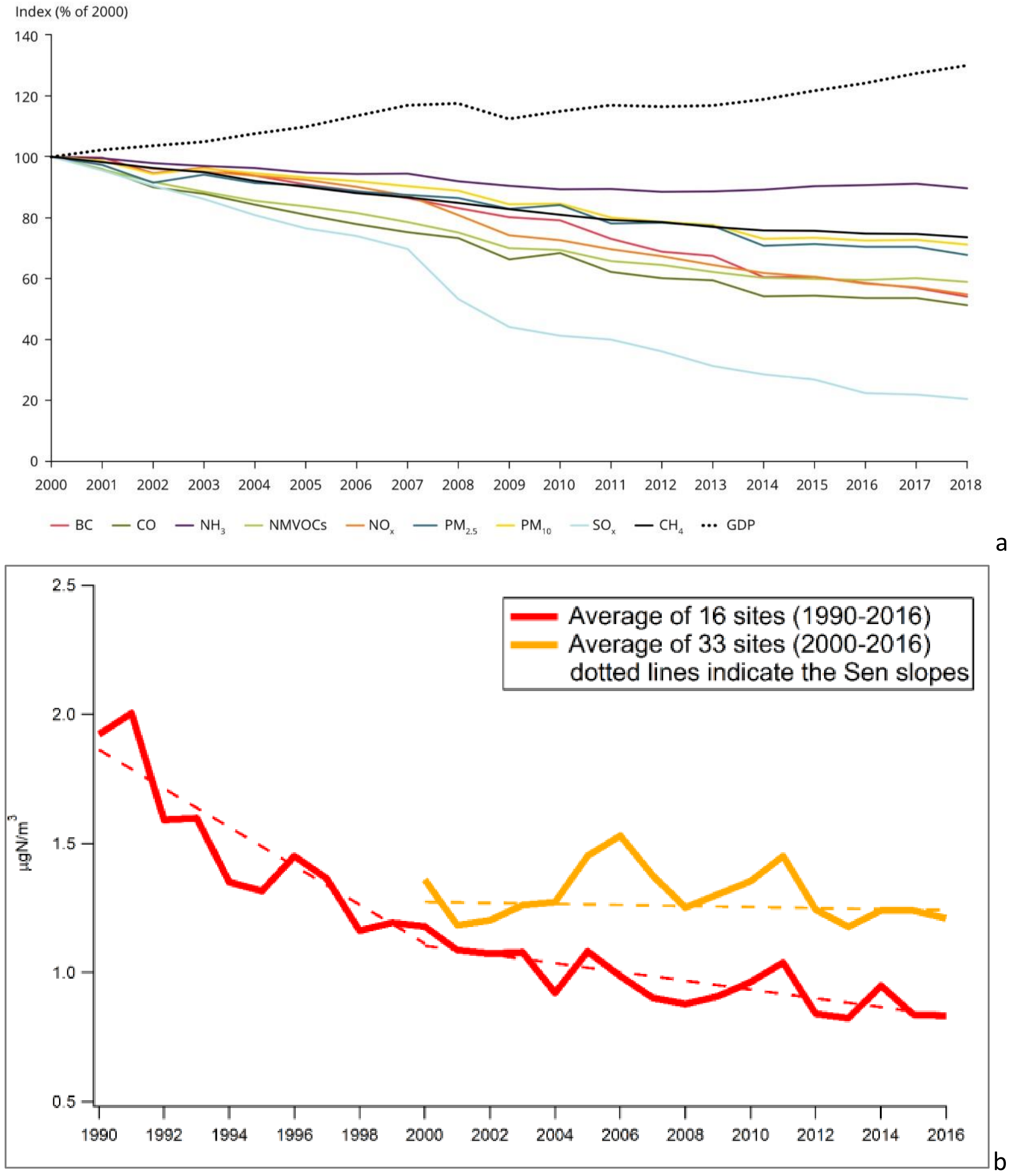

Figure 4: (a) Trends in EU-28 emissions, 2000 = 100: ammonia is the second line from the top; Sulphur is the lowest (EEA)[16] and (b) average European reduced nitrogen concentrations in air and aerosols at EMEP-background stations (sum of NH3 and NH4 in µgN/m^3) (EMEP - Chemical Coordination Centre) Note that background measurement stations are not representative for areas with high livestock density.

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 sulphur dioxide, nitrogen oxides and primary particulate matter, where substantial commitments to reduce emissions over the period 2020 to 2030 have been made.[17]

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[16] EEA (2020) Air Quality in Europe – 2020 report, EEA-report No 09/2020

[17] 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)

The European Union and several countries have defined the WHO-guideline value[18] for PM2.5 as their long term target (e.g. see the Clean Air Programme for Europe - EC, 2013). However, from the source apportionment of PM2.5 concentrations (figure 3) it is clear that in many cities meeting the WHO Air Quality Guideline value for PM2.5 will not be possible without substantial reductions in emissions of ammonia, nitrogen oxides and sulphur dioxide in the wider region. For nitrogen oxides and sulphur dioxides EU-wide emission reductions of around 60% (between 2005 and 2030) are obliged under the revised NECD, but for ammonia the reduction obligation is only 5% (before 2030) up to 15% (after 2030). There are large variations in emission reduction obligations among countries (see table 1). 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 NEC-directive for selected countries[19] (in percentages of the 2005 level)

	NH_3		NO_x		SO_2		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
EU 28	6	19	42	63	59	79	22	49

Source: Directive (EU) 2016/2284 of the European Parliament and the Council, December 2016

The formation of secondary particles can be reduced via emission reduction of either nitrogen oxides and sulphur dioxide or of ammonia, or both. For the formation of a particle of ammonium nitrate in the air, one molecule of ammonium and one molecule of nitrate is needed (and two molecules ammonium and one sulphate for a particle of ammonium sulphate). Due to decreasing availability of nitrogen oxides and sulphur 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 particulate ammonium concentrations.[20] 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.[21] Conversely, overall removal rates of ammonia by the ground (through dry deposition) may decrease, due to the less acidic surface.[22] The net result may be that emitted ammonia has a longer atmospheric residence time, leading to larger ammonia concentrations (Tang et al., 2019) and nitrogen deposition in locations remote from sources. While this may end up having some benefits for carbon sequestration by forest areas distant from agricultural land[23], it is also

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[18] The WHO advices to reduce PM2.5 exposure to 10 µg/m^3 as annual mean.

[19] *In the final version all tables will be extended to cover all countries*

[20] 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/

[21] 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]

[22] 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

[23] 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,

expected to come with a cost for sensitive biodiversity. What is clear is that ammonia and ammonium nitrate are now dominating the inorganic air pollution load across Europe.[24]

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% 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.[25]

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), emissions of nitrogen oxides from agricultural land (see figure 5).

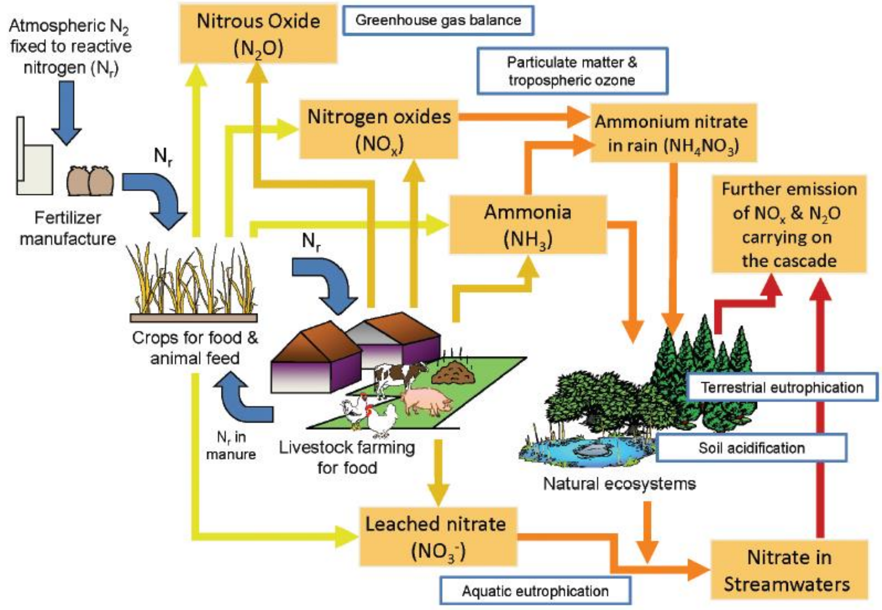

Figure 5: Simplified view of the cascade of nitrogen flows nitrogen from agricultural sources (From Summary for Policy Makers of the European Nitrogen Assessment [26])

An integrated policy strategy is needed to avoid that ammonia reduction measures would increase other nitrogen related problems, and to optimize potential synergies. From a field perspective on its

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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

[24] Tang et al. (2020) Pan-European rural atmospheric monitoring network shows dominance of NH3 gas and NH4NO3 aerosol in inorganic pollution load. Atmos. Chem. Phys. Discuss. https://doi.org/10.5194/acp-2020-275

[25] 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.

[26] Sutton et al. (2011) Summary for Policy Makers. In: The European Nitrogen Assessment, pp xxiv-xxxiv, Cambridge University Press.

own ammonia emissions could be reduced with deep injection of manure on grassland, but the risks are an 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.[27]

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 could enhance methane emissions, and vice versa. 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.[28] 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.

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[27] 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 www.unenvironment.org/resources/frontiers-201819-emerging-issues-environmental-concernfrontiers

[28] 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/

3. Sources and abatement measures

Manure from livestock farming is responsible for more than 70% of the emissions of ammonia in Europe. The use of mineral fertilizer in agriculture contributes 20% to the ammonia emissions. Traffic, industry and people make up the other 10%. In Europe around 50% of the emissions from livestock come from cattle, 30% from pigs and 20% from poultry.[29] In some countries new ammonia emission sources e.g. from the application of sewage sludge and of digestates from energy crops, are growing fast.

Housing (40%), storage (20%), application (35%) and grazing (5%) are the main stages in the manure-chain that cause ammonia emissions (see figure 6a). 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% of the total technical abatement potential.[30] In France, ADEME estimated that direct incorporation and injection will form 60% of the total abatement potential in France (Mathias et al, 2013).[31] See figure 6b.

The UNECE Task Force on Reactive Nitrogen has prepared a draft guidance document on Integrated Sustainable Nitrogen Management, which puts ammonia emission reduction in the broader context of more efficient use of nitrogen in agriculture.[32] 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)[33]. The remainder of this paragraph builds upon these documents.

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 would replace the use of mineral fertilizer in agriculture, it would also reduce the total costs of the ammonia emission reduction strategy.

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

[30] 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

[31] 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

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

[33] 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=The%20Ammonia%20Framework%20Code%20is,Ozone%2C%20and%20its%202012%20amendment 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

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.

The challenge is to convince farmers that manure is a valuable nutrient resource, 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 a recording of the amount of manure that is used will be required. Also, transport of manure from livestock farms to arable land will have to be organised. Ideally import and export of nutrients via trade is in balance in a country or region. 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% of the nitrogen that was imported via food, feed and mineral fertilizers was exported in the form of agricultural products (meat, dairy and vegetables)[34]. The rest (48%) was lost to air, water and soil. This looks bad, but considering that in 1990 only 30% 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.

An integrated nitrogen approach could especially be financially attractive for modern large scale farmers. According to IIASA, 80% of the manure in Europe is produced by 4% of the farms. 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 in middle and large size farms.[35]

In areas with many small scale farms, e.g. in eastern Europe, 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. According to the draft Guidance Document on Integrated Sustainable Nitrogen Management[36] low costs measures in such areas can be 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.

According to IIASA, technically more ammonia emission reduction is feasible than agreed under the NEC-directive, e.g. up to 50% reduction in Germany.[37] The optimal strategy where additional marginal costs would equal marginal benefits would allow for ammonia reductions of up to almost 40% in Germany and 30% in France (see table 2).

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.[38]

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

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

[35] 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

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

[37] 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

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

ammonia.[39] Measures would include further housing adaptation and deep injection of manure. The use of gas scrubbers for purifying the air from stables currently form the high end of the cost-curve, with costs up to € 15 per kg ammonia.[40] Further investment 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.[41] 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 level 2005 in mln kg	reduction percentages			
		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
EU28	3982	6	19	27	35

IIASA (2014)

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

[40] 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

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

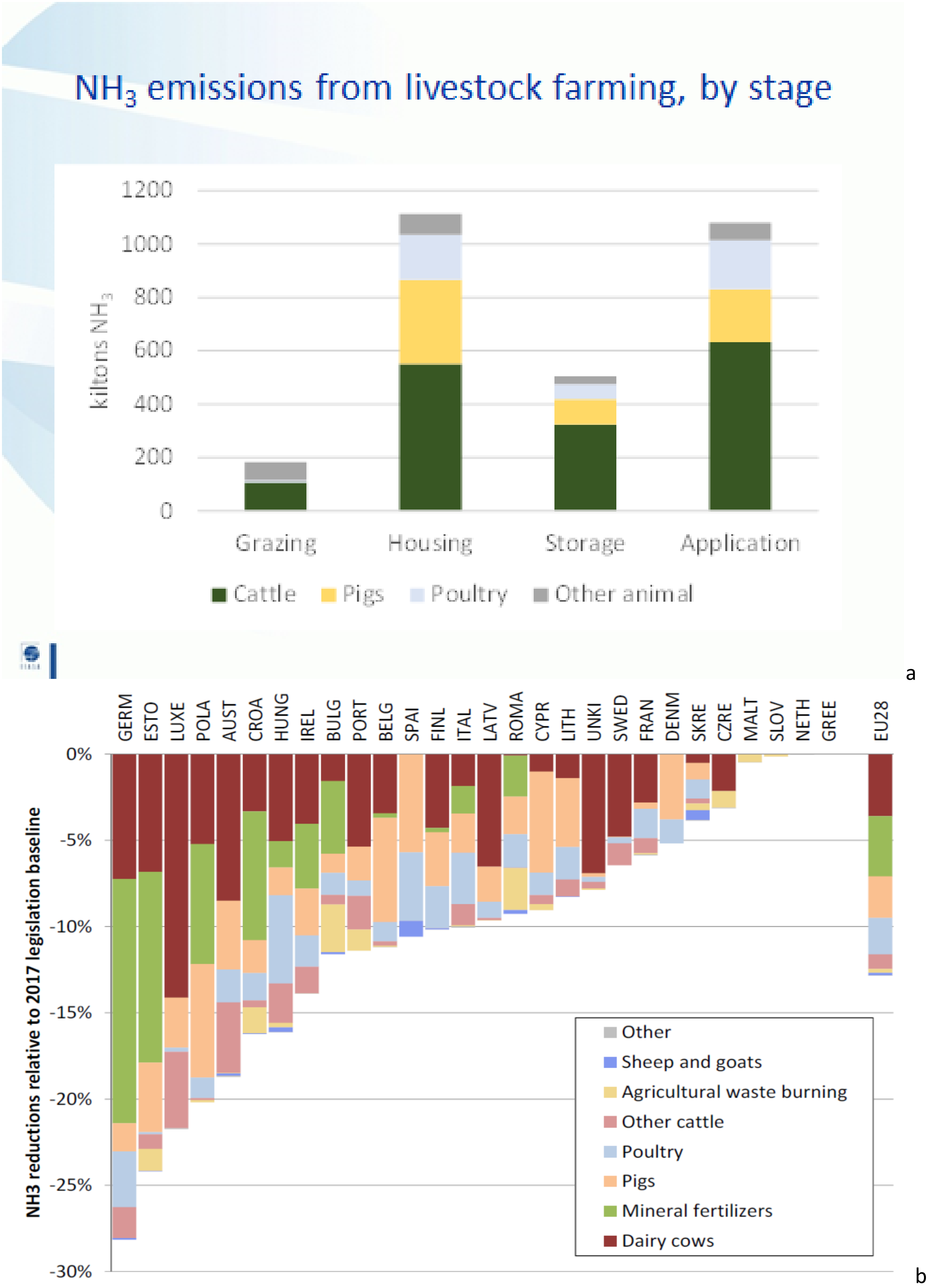

Figure 6: Main sources of ammonia emissions (a) and ammonia reductions up to 2030 implied by the EU-National Emissions Ceilings directive (b) (IIASA, 2017)[42]

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

The nitrogen debate in the Netherlands

From 2016 ngo's challenged the existing nitrogen policy in the Netherlands in legal courts. In May 2019 the supreme court of the Netherlands blocked new permits for all activities that cause additional nitrogen deposition. In November 2018 the European Court of Justice had judged that permitting in the Netherlands was not in line with the Habitat Directive of the EU and would lead to further increase of nitrogen deposition, although all permits included European emission limit values, the obligations under the National Emissions Ceilings Directive were met, as well as the obligations under the Nitrate Directive. The construction of new animal housing, roads, houses and other buildings had to stop at once. This caused massive protests of both farmers and construction workers. Highway blockades caused traffic chaos across the country for several days. Farmers put the conclusion that ammonia was a dominant cause of biodiversity loss into doubt. Committees were formed to develop a way out and to scrutinize the data and models. The lesson was that the Habitat Directive should be taken more serious. And that what happened in the Netherlands could also happen in courts in other EU-countries.

From now on, permits for new activities can only be given after a reduction of current nitrogen depositions. Of the reduced nitrogen deposition 70% can be used for new permits. The remaining 30% defines the speed of reduction in excess nitrogen deposition. The main problem in the Netherlands is the high density of livestock and traffic and the scattered pattern of small nature areas. The scope for additional technical measures is very limited. That means that most probably the solution will have to be found in reduction of activity levels. The first easy measures were taken were the reduction of the speed limits on highways, additional funding for nature conservation and financial incentives to voluntary close pig stables. But the reduction of the cattle stock is still debated heavily. Some farmers promote new high tech solutions (e.g. cows with a higher milk productivity, additives to cattle feed and 'innovative' housing systems). Other farmers choose low tech solutions: lower cattle densities and more grazing would mean less ammonia, less methane, healthier cows, but with a lower productivity.[43] However they would also require less cattle feed, less fertilizers and less antibiotics.

Lessons from the Netherlands and Flanders learn that enforcement of regulation is essential for an effective implementation of ammonia abatement measures. E.g. the installation of air scrubbers itself proved to be insufficient as they were not always operational and additional measures had to be taken to guarantee its use. Recording of manure transport also remains to be a challenge to prevent groundwater pollution or illegal export and dumping. Transboundary co-operation is needed to make national import and export data of manure consistent. Current inconsistencies indicate that ammonia emissions might be underestimated. Better recording would increase the effectiveness of ammonia emission reduction measures and could avoid increased concentrations of nitrate in groundwater.

Urea fertilizer

Low emission manure application can have a large contribution to reducing ammonia emissions, especially when combined with less mineral fertilizer use. One of the types of mineral fertilizer that contributes relatively much to ammonia emission is urea fertilizer. This type of fertilizer is relatively cheap and widely used in Germany, where the share of fertilizer use in the total ammonia emissions is around 25%. Substitution of this type of fertilizer is a cost-effective measure (€ 0.1-2.8 per kg ammonia) (Wulf, et al. (2017) – see footnote 38). In Germany, since January 2020, all urea fertilizer must be immediately incorporated into the soil or incorporate special compounds to slow urea break down ('urease inhibitors'), both of which substantially reduce ammonia emissions.

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[43] According to the Emission Inventory Guidebook both ammonia and methane emission factor is substantially lower for manure excretion in meadows than in stables.

Ammonia and methane: synergies and trade offs

European climate policy is set for further ambition and action on the time horizons to both 2030 and 2050 as part of the European Green Deal proposals. Renewables and electrification offer a challenging but comparatively clear path for many sectors to decarbonise. In contrast, agriculture and biogenic methane remain comparatively unconstrained. Whilst reducing herd sizes and changing global diet patterns would have a direct impact, the former is highly contentious politically, and the latter would require a coordinated global population response. As outlined in this report, ammonia is also a particular challenge in an air pollution context for many member states, and, as with biogenic methane, is something which should be addressed within the agriculture sector. Choices, co-benefits and trade-offs between ammonia and biogenic methane abatement are researched and merit more direct analysis and policy attention.

As an example promising feed measures for biogenic methane control may be available to herds in feedlot systems, but what are the trade-offs for ammonia and animal welfare? What options are there for grass fed herds? At present countries such as New Zealand have introduced ranges for their biogenic methane target in direct acknowledgment of the uncertainty around plausible pathways for the future. They also recognise the value of reductions in a comparatively short-lived climate forcer as part of efforts to keep global temperature increase well below 2 degrees C.

Anaerobic digestion is also a measure that contributes to replacing fossil fuels by biogas, but does not reduce ammonia emissions or could even increase ammonia emissions if more energy crops are grown and more mineral fertilizer is used.

The integrated assessment of ammonia and climate policies offers the opportunity to build the evidence base for what is possible, or indeed not possible with respect to simultaneously meet ammonia and climate goals in future policy preparations.

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 shows loss in average life expectancy due to exposure to the total PM2.5 concentration. In the countries concerned approximately half of the PM2.5 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.

Table 3: Loss in life expectancy due to PM2.5-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
EU-28	8.5	5.0	4.1	3.6

IIASA (2014)

Table 4 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, what 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	2030 - Cost-optimal	2030 – technically feasible
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%
EU-28	24%	35%	42%

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

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 thought not to be feasible, as is it 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.[44]

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 comprehensive approach. This 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 the meat consumption would reduce ammonia emissions by 43%.[45] That would also significantly reduce emissions of greenhouse gasses and require less land.

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

[45] 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/EPNF%20Documents/Nitrogen_on_the_Table_Report_WEB.pdf

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.[46]

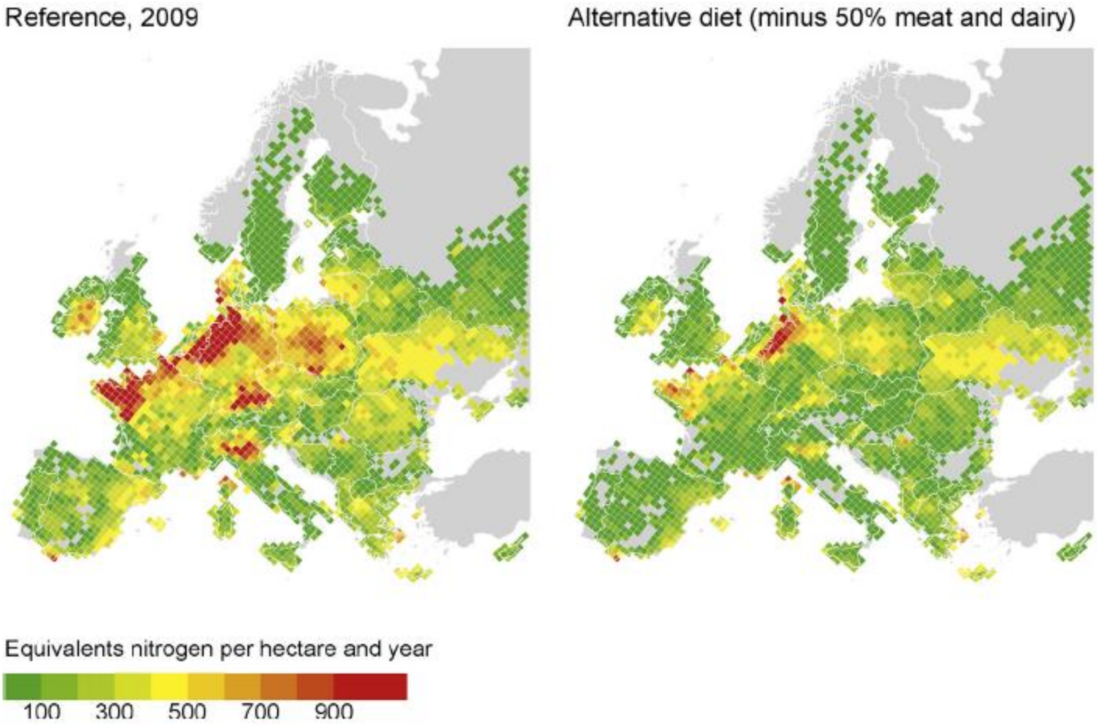

Figure 7: Annual exceedance of the critical load for N deposition in N per hectare for natural ecosystems, under the reference scenario and the 50% less meat and dairy alternative diet (from: Westhoek et al. 2015)

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[46] 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

4. Costs of policy inaction

Current agricultural practices lead to a loss of valuable nutrients. If farmers would adopt an integrated approach to nitrogen and work towards a "circular" agricultural system, less nitrogen would be lost at the farm level and farmers would need to buy less mineral fertilizer. Currently 15 billion euro per year is spend in the EU to buy fertilizers. According to the European Nitrogen Assessment 50% of the nitrogen fertilizer use is wasted. Halving the use of fertilizers would save US$100 billion globally according to UNEP.[47] Moreover, for the society as a whole less nitrogen losses could reduce the damage to public health and ecosystem services. And it 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.

Current damage in the EU to ecosystems and human health due to ammonia emissions was monetized by CE-Delft.[48] These external damage costs are not included in the 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[49] and the valuation of ecosystem damage[50] An extensive methodological description can be found in: de Bruyn et al. (2018)[51]. 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 amongst others on the population density: In Belgium, Netherlands and Germany the damage is estimated at around €30 per kg ammonia, while in Ireland, Spain and Finland the damage is less than €10 per kg.[52]

Studies for specific countries often show lower figures as they don't take into account the impacts on other countries.[53]

Using the CE-Delft estimates, the damage due to the remaining European agricultural ammonia emissions in 2030 would amount to almost **60 billion euro** per year (35-85 billion)[54]. This is 15% of

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[47] UNEP Frontiers Report: The Nitrogen Fix: https://apo.org.au/sites/default/files/resource-files/2019-03/apo-nid224376.pdf. See also: European Nitrogen Assessment: Sources, effects and policy perspectives (eds. Sutton et al., 2011, Cambridge University Press - http://www.nine-esf.org/node/360/ENA-Book.html

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

[49] 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

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

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

[52] 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

[53] 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

[54] This estimate is lower than 70-320 billion euro 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.,

the total agricultural output and more than 50% of the annual income (net value added) from agricultural activity in the EU.[55] Note that the agricultural sector in Europe also receives a net subsidy of around 35% of the net value added to keep food prices low.

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

The damage cost estimate of €17.50 per kg ammonia is higher than the abatement cost estimates. According to the German study (Wulf et al, 2017), the average costs of ammonia abatement would be € 0-4 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.

Including the damage costs in the prices of food, would lead to a price increase of meat and dairy products. According to CE-Delft[56] a true price of beef and pork that includes the environmental damage from nitrogen losses, would have to be 25-35% higher. Raising the prices of meat and dairy products would lead to an increase of the costs of meals, which can be problematic for low income groups. However, such an increase in the costs of meals could be limited, if higher meat and dairy prices are combined with campaigns aimed at dietary change.

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 .

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

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

5. Conclusions and recommendations

Ammonia emissions, concentrations and deposition in Europe show a moderate decline over the last 15 years compared to sulphur dioxide and nitrogen oxides. 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 revised NEC-directive, are still possible. Abatement costs of ammonia are significantly lower than the damage per kg, and vary from € 0-4 per kg ammonia for most countries, up to € 15 per kg ammonia in some areas with a high density of livestock.

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 made of manure transports in order to avoid conflicts with nitrate leaching.

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 would be combined with less mineral fertilizer use.[57] Low emission manure application is currently the most effective abatement option e.g. for Germany and France to reduce ammonia emissions.

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."

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.

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 also reduce methane emissions. Less use of mineral fertilizers would have benefits for both air quality and climate. For the production of mineral fertilizer large amounts of natural gas are needed, and the use of mineral fertilizers contribute to emissions of nitrous oxide.

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

Because of the transboundary role of ammonia in the formation of secondary particulate matter and nitrogen deposition on ecosystems, it is important to continue the exchange of information on abatement policies. Clarity in the timing of envisaged ammonia abatement measures would help neighbouring countries to underpin their national air quality plans with quantitative estimates.

Annex 1: Ammonia assessment for Canada and the United States

Emissions of most air pollutants have been on the decline in Canada and the United States 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% of the US population lives in areas that exceed ambient air quality standards for fine particulate matter (PM2.5)[58]. Emissions of ammonia are of concern in Canada and the United States as atmospheric ammonia is a key precursor to the formation of fine particulate matter (PM2.5) and contributes to acid deposition and eutrophication. The health effects of atmospheric PM 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. The United States and Canada have had a long history of cooperation on monitoring and assessment of acid deposition[59] , including under the 1991 Canada-United States Air Quality Agreement.

While much progress has been made in the last two decades in reductions of other precursors to PM2.5 such as NO_x and SO_2, emissions, and correspondingly atmospheric concentrations, of ammonia have continued to rise in both Canada and the US. In both countries, the agricultural sector is the dominant source of ammonia, accounting for 93% of national emissions (Canadian Air Pollutant Emissions Inventory, 2020; US EPA National Emission Inventory, 2020). Areas of intense agricultural activity include southern Ontario and Quebec, southern British Columbia, Alberta, Saskatchewan, as well as the Midwestern US, California and North Carolina. Ammonia emissions near the Canada-United States border also have transboundary impacts on air quality (Figure 1). More detailed assessments are needed to quantify the impacts.

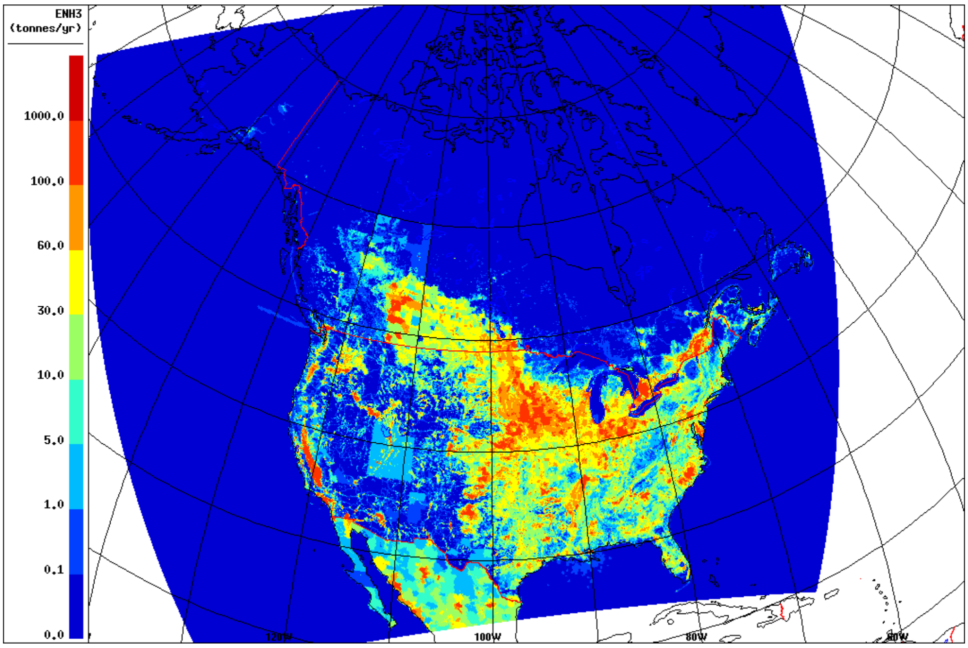

Figure 1: Annual North American Ammonia Emissions (tonnes/grid cell)
(based on 2013 Canadian and 2017 projected U.S. inventories, 10 km x 10 km GEM-MACH grid)

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

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

Ammonia emission trends in Canada

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

Two distinct trends are observed in Canadian national ammonia emissions (Figure 2). The first is a consistent rise in emissions from crop production, which more than doubled between 1990 to 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.

The second distinct 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% of Canada's total ammonia emissions in 2005. In 2018, they made up 59%. 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.

These two counter-acting trends in the past decade have resulted in modest fluctuations to Canada's overall national ammonia emissions. While Canada's emissions have increased 21% 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, Canada's ammonia emissions overall will increase over the coming decade due to continued increase in nitrogen-based fertilizer application for crop production.

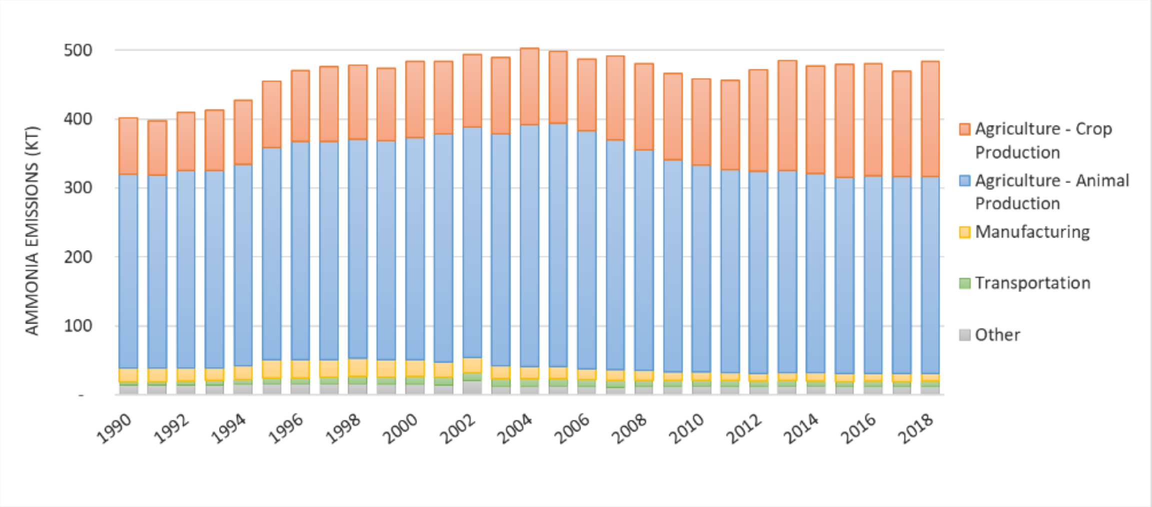

Figure 2: Estimated annual ammonia emissions for Canada (national total)

Ammonia emissions in the United States

In the United States in 2017, approximately 59% of ammonia emissions is attributed to agricultural livestock. The next largest categories are fertilizer application (21%) and agriculture fires and prescribed burning (5%). A combination of other emission source categories, including fuel combustion, industrial processes, and waste management, contribute the remaining 15% of the total[60].

Ambient concentrations and acid deposition

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.[61] Although decreased ammonia emissions have been reported in some provinces and states across Canada and the United States, increasing trends in emissions at the national level and in ammonia concentrations have been identified from satellite observations and ground-level measurements.[62,63]

The National Atmospheric Deposition Program (NADP) (including National Trends Network (NTN), Atmospheric Integrated Research Monitoring Network (AIRMoN), Clean Air Status and Trends Network (CASTNET), and Canadian Air and Precipitation Monitoring Network (CAPMoN) are the primary networks supporting nitrogen deposition assessments in Canada and the United States. Other air monitoring networks measuring atmospheric nitrogen include the Ammonia Monitoring Network (AMoN) under the NADP, the Interagency Monitoring of Protected Visual Environments (IMPROVE), the Canadian National Air Pollution Surveillance Program (NAPS) 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^+) of reduced nitrogen to reduce the overall uncertainty in the chemical formation of $PM_{2.5}$ and transport and deposition of reduced nitrogen compounds.

Increasing trends in annual ambient ammonia concentrations were observed at NADP/AMoN sites across Canada and the United States, with the percentage increases exceeding 40% in the last 8-13 years[64]. Established in 2007, the NADP/AMoN is the only network providing a consistent, long-term record of ambient ammonia concentrations across the United States and at some sites in Canada. These ground-based measurements have been used to validate satellite observations showing similar trends with improved spatial coverage (Figure 3). 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 sulphate and nitrate converting ammonia to ammonium; and changes in meteorological conditions.[3]

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

[61] 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).

[62] 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).

[63] 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)

[64] 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

Deposition of reactive nitrogen is highest in central and eastern Canada and the central United States. 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 sulphates are declining due to reduction of precursor emissions (sulphur and nitrogen oxides).However, while wet deposition of sulphate and nitrate have also declined, wet deposition of ammonium has not changed significantly since 1990 (Figure 3). Further work is required to assess how particulate ammonium interacts with other pollutants. In the US, wet deposition of oxidized nitrogen has declined in nearly all states, but from 1990-2010, ammonium wet deposition has increased in 37 of the 45 states where monitoring is available[65].

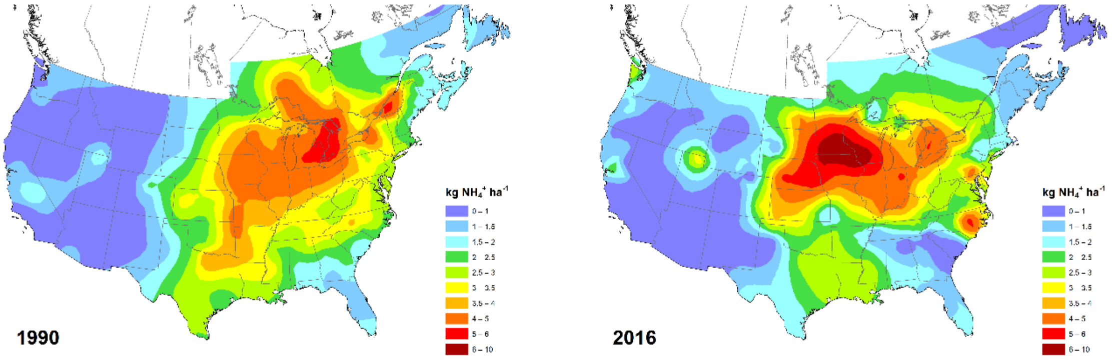

Figure 3: Observed annual wet deposition of ammonium in 1990 (left) and 2016 showing areas between Canada and the US where transboundary ammonia emissions may require further assessment. Interpolated surface based on data from U.S. National Atmospheric Deposition Program National Trends Network and Canadian Air and Precipitation Monitoring Network.

Abatement measures

Ammonia continues to be a major contributor to secondary $PM_{2.5}$ particularly in eastern Canada and the central United States, through the reaction of NH_3 with oxides of sulphur and nitrogen (SO_x and NO_x) to form ammonium sulphate and ammonium nitrate. As a result, during high pollution events ammonium can in some regions, account for up to 25% of the $PM_{2.5}$ mass. With the reported and observed increases in Canadian and United States 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)[66].

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 nation-wide guidelines on agricultural practices,

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[65] 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

[66] 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

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 moved towards improved nitrogen use efficiency over the years (including several practices accepted as mitigation methods by the UNECE[67]), due primarily to practical or economic reasons.

In October 2018, Environment and Climate Change Canada held an ammonia workshop that brought together scientists and policy makers from Canada, the United States 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.

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

Annex 2: Ammonia policy in Eastern Europe, Caucasus and Central Asia

In large parts of Russia, Ukraine and Belarus critical loads for nitrogen are exceeded. In the European part of Russia 40-50% of the ecosystems are at risk. In Belarus and Ukraine this is almost 100%.[68] 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.

Experiences of ammonia policies in EECCA countries are described in van der Hoek and Kozlova[69]. 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 are rising slowly. In Russia the available nitrogen in manure (organic fertilizer) was reduced by more than 85% and agricultural ammonia emissions from husbandry in the European part of Russia were reduced by 60% [70]. 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[71].

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-sulphate.[72]

Cattle densities in eastern Europe, central Asia and the Caucasus are lower than in western Europe. Compared to Russia and central Asia, 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 Russia, currently around 80% of the nitrogen input to agricultural land comes from mineral fertilizers[73].

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%. But the costs seem still to be prohibitive for farmers. Implementation is stimulated via pilot projects[74].

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