Abating N in Nordic agriculture - policy, measures and way forward

Sofie Hellsten[1], Tommy Dalgaard[2], Katri Rankinen[3], Kjetil Tørseth[4], Lars Bakken[5], Marianne Bechmann[6], Airi Kulmala[7], Filip Moldan[1], Stina Olofsson[8], Kristoffer Piil[9], Kajsa Pira[10] and Eila Turtola[11].

[1] IVL Swedish Environmental Research Institute, P.O. Box 5302, SE-400 14 Gothenburg, Sweden.
[2] Aarhus University, Department of Agriculture, DK-8830 Tjele, Denmark.
3Finnish Environment Institute, P.O. Box 140, FI-00251 Helsinki, Finland.
4NILU – Norwegian Institute for Air Research, P.O. Box 100, NO-2027 Kjeller, Norway.
5 Norwegian University of Life Sciences, P.O. Box 5003, NO-1432 Ås, Norway.
6 NIBIO, Norwegian Institute of Bioeconomy Research, P.O. Box 115, NO-1431 Ås, Norway.
7Central Union of Agricultural Producers and Forest Owners (MTK), PO Box 510, FI-00101 Helsinki, Finland.
8 Swedish Board of Agriculture. Department of Plant and Environment. P.O. Box 12, SE-230 53 Alnarp, Sweden
9SEGES Danish Agriculture & Food Council F.m.b.A.,Agro Food Park 15, DK-8200 Aarhus N, Denmark
10Air Pollution & Climate Secretariat, Första Långgatan 18, SE-413 28 Gothenburg, Sweden
[11]Natural Resources Institute Finland (Luke), Tietotie 4, FI-31600 Jokioinen, Finland

Keywords: Nordic countries; reactive nitrogen; nitrogen management; nitrogen policy; ammonia emissions; nitrogen surplus

Abstract

During the past twenty years, the Nordic countries (Denmark, Sweden, Finland and Norway) have introduced a range of measures to reduce losses of nitrogen (N) to air and to aquatic environment by leaching and runoff. However, the agricultural sector is still an important N source to the environment, and projections indicate relatively small emission reductions in the coming years.

The four Nordic countries have different priorities and strategies regarding agricultural N flows and mitigation measures, and therefore they are facing different challenges and barriers. In Norway farm subsidies are used to encourage measures, but these are mainly focused on phosphorus (P). In contrast, Denmark targets N and uses control regulations to reduce losses. In Sweden and Finland, both voluntary actions combined with subsidies help to mitigate both N and P.

The aim of this study was to compare the present situation pertaining to agricultural N in the Nordic countries as well as to provide recommendations for policy instruments to achieve cost effective abatement of reactive N from agriculture in the Nordic countries, and to provide guidance to other countries.

To further reduce N losses from agriculture, the four countries will have to continue to take different routes. In particular, some countries will need new actions if 2020 and 2030 National Emissions Ceilings Directive (NECD) targets are to be met. Many options are possible, including voluntary action, regulation, taxation and subsidies, but the difficulty is finding the right balance between these policy options for each country.

The governments in the Nordic countries should put more attention to the NECD and consult with relevant stakeholders, researchers and farmer's associations on which measures to prioritize to achieve these goals on time. It is important to pick remaining low hanging fruits through use of the most cost effective mitigation measures. We suggest that N application rate and its timing should be in accordance with the crop need and carrying capacity of environmental recipients. Also, the choice of application technology can further reduce the risk of N losses into air and waters. This may require more region-specific solutions and knowledge-based support with tailored information in combination with further targeted subsidies or regulations.

1. Introduction

The supply of nitrogen (N), being an essential nutrient, has been vitally important for increased food production to support the growing global population and the diet change over the past century (Battye et al., 2017).

The Haber-Bosch process, which transforms atmospheric N_2 to form reactive N (ammonium and nitrate), made it possible to intensify agriculture and increase food production. As a result, industrially produced mineral fertilizer is today the largest source of reactive N in Europe (Sutton et al., 2011). During the past six decades, anthropogenic production of reactive N in the world has increased almost five-fold (Battye et al., 2017). Organic material like manures or root nodules of leguminous, and deposition of N from the air, also provide N into the soil along with the easily soluble nitrate compounds or ammonium-nitrates from inorganic fertilizers. Organic N can be mineralized to ammonium and nitrates by microbial reactions in soil.

Reactive N, derived from both fertilizer and organic compounds, may contribute to several environmental effects. This occurs through emissions to air (ammonia NH_3, nitrous oxide N_2O and nitrogen oxides NO_X), and to water, (nitrate NO_3^-, organic N, ammonium NH_4^+ and NH_3 by deposition) affecting ecosystems, climate and human health (e.g. Galloway et al., 2003; Krupa, 2003; Erisman et al., 2013; Sutton et al., 2009; 2011; 2013). For instance, Leip et al. (2015) estimated that the agricultural sector in Europe contributes to 59% of N water quality impacts.

In the Nordic countries, the level of N related problems varies. Denmark has the highest N-loss per national area compared with the other Nordic countries, due to the high percentage of agricultural area (62%), see Table 1. Also, Denmark has the largest meat production, particularly from pigs. The meat production in Sweden is only about 30% of the total production in Denmark, and in Finland and Norway it is even smaller (about 20%), see Table 1.

Table 1. Agricultural statistics in the Nordic countries; agricultural land, nitrate vulnerable zones (NVZ), meat production and N surplus from agricultural land. Source: FAO FAOSTAT, Eurostat (http://ec.europa.eu/eurostat) and SSB (www.ssb.no). Data refer to 2015 or more recent years.

	Total landarea (km^2)	Agricultural land (km^2)	NVZ (km^2)	Meat production* (thousand tonnes)					N surplus (kg ha^{-1})	Total N surplus (ktonnes)
				pig	cattle	poultry	sheep	Total		
Denmark	41,990	26,110 (62%)	26,110 (100%)	1,530	124	164	2	1,820	80	209
Sweden	407,310	30,398 (7.5%)	22,800 (75%)	240	132	159	5	536	32	97
Finland	303,910	22,734 (7.5%)	22,734 (100%)	179	85	129	1	395	49	111
Norway	365,245	9,061 (2.5%)	2,712 (30%)	137	85	101	27	351	100	91

*Only includes slaughtered animals.

A higher share of farm land, intensive livestock production (primarily pigs), higher farming intensity and the sandy soils have contributed to more severe N problems in Denmark compared with the other Nordic countries. Consequently, from 1985 a series of political action plans were implemented in Denmark to mitigate losses of N and other nutrients (Dalgaard et al., 2014).

In Finland, the concerns about eutrophication arose by the 1960's, and increasingly since 1995 a set of legal and voluntary instruments have been implemented, targeting agricultural nutrient losses to waters. Previously, increased N inputs and clearing forested land to develop new fields gradually increased agricultural N losses in Finland. However, between 2007 and 2012 N loads from agriculture were reduced by 10% (Rankinen et al., 2016).

In Norway, during the 1980's and 1990's, a system of regulation and economic instruments coordinated by local authorities was developed to encourage farming practices that would reduce diffuse sources of nutrients from agricultural land and point sources such as silos and manure storage systems. The economic instruments have focused mainly on mitigation measures for losses of phosphorus (P) with a side effect on N. The system has been fine-tuned over the years to target areas with high risk of erosion and P losses. However, due to low focus on N, surpluses per agricultural land area are generally higher in Norway compared with the other Nordic countries, see Figure 2.

In Sweden, legislation on storage and spreading of manure was introduced by the 1980's and expanded in subsequent years. The measures have targeted reductions of both N and P. In 2001, the voluntary advisory program "Focus on Nutrients" ("Greppa Näringen") was initiated in order to meet national environmental objectives including reduced eutrophication and climate change. Support schemes within the Rural Development Program (RDP), e.g. for catch crops, have also been important to reduce nutrient loads to air and waters.

The aim of this study was to compare and discuss the present situation pertaining to agricultural N in the Nordic countries as well as to provide recommendations for strategies and policy instruments to achieve cost effective and balanced abatement of reactive N from agriculture in the Nordic countries, and to provide guidance to other countries.

2. N management in the Nordic countries

2.1 Measures to reduce ammonia emissions

Since agriculture emits most of the ammonia in Nordic countries, the agricultural sector must promote emission reductions. An overview of measures to reduce ammonia emissions in the Nordic countries, and level of implementation, is provided in Table 2.

Table 2. Overview of measures to reduce ammonia emissions in the Nordic countries. The costs are representing € per kg N reduced, and are primarily based on cost estimates from Sweden and Denmark. Updated from Hellsten (2017).

Measure	Denmark	Sweden	Finland	Norway
Low N feed Reduces ammonia emissions at many stages of manure management, from excretion in livestock houses, through storage of manure to application on land, including grazing. Also positive effects on animal health and indoor climate. This measure could be increased by providing information and counselling about low N feed or phase feeding (i.e. the protein content of the feed is adjusted over the lifetime of the livestock). **Reduction potential:** about 20% (van Vuuren et al., 2015). **Cost:** -0.5 - 0.5 € (van Vuuren et al., 2015).	Phase feeding of livestock has been successful in reducing ammonia emissions from the pig industry. For instance, crude protein level recommendations for grower finisher pigs are 14.2-16.5% depending on weight (Tybirk, 2015). Phase feeding is used for almost all sows and piglets, but only for 30-40% of finishers. In dairy production with automatic milking systems (~25% of Danish dairy farms), dairy cows are allocated protein feed based on milk yields.	Crude protein levels in pig feed have been low since 1990. Feed for a standard growing-finishing pig in Sweden generally contains 14.5% crude protein (Botermans et al., 2010). Therefore the potential to reduce ammonia emissions is limited. Botermans et al. (2010) have estimated a 20% reduction in ammonia emissions if the crude protein level would be further reduced to 12.5%.	Phase feeding is utilized and the advisory systems deliver information on N requirement during different feeding phases.	No policy regarding low N feed exists in Norway.
Low emission housing Measures to reduce the surface area and time manure is exposed to air, e.g. design of the stable and manure handling system. Most efficient and cost effective for new livestock houses. This measure could be increased by regulations regarding new livestock houses. However, effect of housing design on animal welfare needs to be considered, e.g. the possibility to have loose dairy and free range poultry. **Reduction potential:** 20-90% (Bittman et al., 2014). **Cost:** 0-20 €[1)] (Bittman et al., 2014; Montalvo et al., 2015).	All countries have applied measures for low housing emissions at varying degree. Large pig and poultry farms are regulated through the Industrial Emissions Directive (IED) applying Best Available Techniques (BAT) Reference document (BREFs) developed under the IED, see Table 6.			
	New or expanding housing must comply to emission standards. Standards vary with distance to protected natural areas. In practice this will require technologies that reduce emissions, e.g. solid floors, frequent removal of manure, manure cooling or acidification or air purification (see below).	”Focus on Nutrients” inform farmers about measures for low emission housing.		
Air purification Options to treat the air ventilated from animal housing, e.g. biological air cleaning or acid scrubbers to treat the exhaust air. Air purification filters are not suitable in all animal buildings, e.g. in buildings with natural ventilation. This measure could be increased by setting rules and demanding air purification in conjunction with permissions for new or expanded operations. **Reduction potential:** About 60% (assuming about 20% of the ventilation capacity). (NIRAS, 2009). **Cost:** 2.5-17 € (NIRAS, 2009).	This is an expensive measure which is not broadly used in the Nordic countries.			
	Air purification may be required to comply with emissions standards for new housing, particularly for pig farms, both with regard to ammonia loss and odour. However, it is not a very common technology even in Denmark.	Swedish animal buildings often have natural ventilation, which is not suitable for air purification filters.		The technique has been implemented on a voluntary basis by a few agricultural producers.
Covered storage Reduce the exposure of stored manure to air, e.g. concrete lid, plastic floating sheet, peat (see below), straw or natural crusts. Stricter regulations regarding cover of slurry, urine containers and also digested manure could be an effective measure. **Reduction potential:** 50-95% depending on type of cover (SBA, 2010). **Cost:** 0.5-5 € (SBA, 2010).	Danish regulations comprise e.g. minimum storage capacity, to comply with slurry close periods, no runoff from manure heaps and mandatory slurry tank covers. Covers can be natural crusts (dairy farming) straw crust (~50% of pig farms) or lids, typically of the “tent” type (~50% of pig production).	Aall livestock farms must have sufficient manure storage. For farms with > 100 animal units, minimum storage capacity is 8 to 10 months depending on animal type. In southern Sweden requirements for coverage of slurry and urine tanks apply. The majority of slurry stores in Sweden are covered (98% year 2013) (Statistic Sweden, 2014), hence the main emission reduction potential is to apply more effective covers than natural crusts.	All new slurry and dry manure storages must be covered and minimum storage capacity is 12 months.	A a minimum storage capacity for 8 months is required, but no cover is required. 20% of storages in Norway are not covered (Bechmann et al., 2016b).
Using peat during storage of solid manure Advantages include more easily spread manure and a better housing environment and animal health. A disadvantage is the trade off with climate change effects and other environmental effects of increased peat extraction. This measure could be increased by providing information and counselling, to facilitate contacts with peat producers or by offering subsidies for agricultural producers using peat. **Reduction potential:** About 50% (SBA, 2010)	The use of peat as litter is very limited in the Nordic countries today.			
		Germundsson (2006) has estimated the use in Sweden to be about 200 000 and 300 000 m^3 per year.	1.6 million m^3 horticultural, bedding and environmental peat was produced in 2017 (Luke, 2018). Iivonen (2008) estimated that the average use of bedding peat in Finland is 1.2 million m^3 $year^{-1}$.	

Cost: About 0.5 € (SBA, 2010).				
Low ammonia application of manure Means to distribute manure to minimize surface exposure, e.g. shallow injection or direct incorporation, see Table 3. **Reduction potential:** 45-90% depending on type of manure and time after spreading (SBA, 2010). **Cost:** About 0.5-1 € (SBA, 2010).	The use of application techniques are enforced by regulations. There are set standards for which application techniques are allowed on which type of fields. Broadcasting has been banned since 2002 and there is also a ban on winter spreading of slurry for spring-seeded crops. Enforcement of these rules rests with the municipalities.	Nitrate sensitive areas have stricter regulations regarding when and how manure spreading must occur, and how quickly the manure should be incorporated into the soil. Subsidies may be provided for direct injection of manure but this is decided by the County Administrator Boards, hence differs within the country.	Manure must be incorporated within 24 hours after spreading, with a few exceptions (e.g. application on plants with a hose sprayer or over an entire area). Stricter regulations, i.e. quicker incorporation, apply on sections of arable land parcels with a slope of at least 15%.	Subsidies are provided for band application and direct injection of manure. The spreading period is limited to Feb 15th to Sep 1st for surface application or Nov 1st for incorporation.
				The application of manure and organic fertilizers in fields is prohibited from Nov 1 to Mar 31 (unless exceptional weather conditions have prevented the use of manure as fertilizer during the growing season). A subsidy for direct injection of slurry into the soil has been available in the RDP for Mainland Finland (2014-2020).
Low emission application of urea fertilizer Refers to appropriate timing and dose of application. Ammonia emissions are reduced if urea is incorporated into the soil or if a urease inhibitor is used. Urease inhibitors reduce ammonia emissions by >30% (Bittman et al., 2014).	In Denmark, 10-20% of mineral N fertilizers is urea.	In Sweden, Norway and Finland, the use of urea in agricultural production is very low, but it may increase in the future if there is a change in price in relation to other fertilizers.		
		Southern Sweden has regulations that urea should be incorporated into the soil within 4 hours.		
Acidification of slurry Lowering the pH of manure (either in housing or prior to application) reduces ammonia emissions. A disadvantage is that the development of biogas production is discouraged. Information activities and subsidies could be possible instruments to encourage the use of acidifying substances. **Reduction potential:** About 80% during storage and 70% during spreading (NIRAS, 2009). **Cost:** 3-14 € (NIRAS, 2009).	Adoption is estimated at 20% of the slurry based on contractor interviews but only 10-12% based on acid sales (Nyord, T., Aarhus University, Denmark pers comm., 2018).	Acidification of slurry is not broadly used in the Nordic countries, except for Denmark. This measure can be used only for slurry. Reducing pH of slurry is difficult to implement in some countries, as liquid manure systems are required (Rodhe et al., 2018).		

1) Includes expensive measures such as air purification.

The Task Force on Reactive Nitrogen (TFRN), a working group of the Convention on Long-range Transboundary Air Pollution (CLRTAP), has summarized a comprehensive listing of techniques to reduce ammonia emissions in the "UNECE Ammonia Guidance Document (UNECE, 2014; Bittman et al., 2014). These mitigation techniques are also summarized in the "UNECE Ammonia Framework Code" (UNECE, 2015). The TFRN has provided a short ranked list of priority measures for ammonia emission reduction, in evaluating options for revision of the Gothenburg Protocol Annex IX (Howard et al., 2015, UNECE, 2011):

1. Low emission application of manures and mineral fertilizers to land.
2. Animal feeding strategies (including phase feeding).
3. Covers on new slurry stores.
4. Farm N balance, i.e. strategies to improve N use efficiencies and reduce N surpluses.
5. Low emission new (and largely rebuilt) pig and poultry housing.

These documents may serve as guidance in the Nordic countries to evaluate potential mitigation techniques. In Denmark (and partly in the other Nordic countries as well) at least number 1 and 3 in the list above have already been implemented. Hence there are limited gains possible from these suggestions for the future.

In agreement with the guidance above, Grönroos (2014) concluded that the most cost effective abatement measures regarding reduction of ammonia emissions in Finland are low emission manure application techniques, feeding strategies and covered storages. Also in Norway, the use of low emission application techniques (e.g. band spreading) has been identified to be efficient measures to reduce ammonia-emissions (Bechmann et al., 2016b). Emission reductions have been estimated to be 1500-2000 tonnes N per year by changing the manure application method from broad spreading to band spreading.

In Denmark, 89% of manure is collected as slurry (Birkmose et al., 2013), whereas the ratio of slurry to FYM (Farm yard manure) is smaller in Norway, 70% (Statistics Norway, unpublished) and Sweden, 62% (Statistics Sweden, 2017). In Finland, all cattle manure is collected as slurry, and 78% of pig manure and 86% of poultry manure (Grönroos et al., 2017). In Denmark, broadcasting has been banned since 2002, but in Finland and Sweden about 35% and 28% of the slurry, respectively, is applied with broadcast spreading, while in Norway 88% of the slurry is being applied using broadcast spreading (see Table 3). This clearly shows a potential to apply more low emission application techniques to reduce emissions of ammonia, such as band spreading and injection, particularly in Norway. In Sweden band spreading has increased steadily during the past 15 years, and the Swedish Board of Agriculture (SBA, 2010) projects that it will continue to increase steadily in the future, even without regulations.

Table 3. Application techniques for slurry in the Nordic countries (%). Updated from Rodhe et al (2018).

Country	Broadcast spreading (%)	Band spreading (%)	Injection (%)
Denmark[1)]	0	85[4)]	15
Finland[1)]	35	34	31
Sweden[2)]	28[5)]	68[5)]	4
Norway[3)]	88	12	0

1) Estimated by national experts
2) Statistics Sweden (2017).
3) Bechmann et al. (2016b).
4) Including 20% acidified slurry.
5) 24% of the surface spread manure (solid and liquid) is incorporated directly, 11% within 4 hours and 9% within 24 hours after spreading (Statistics Sweden, 2014).

2.2 Measures to reduce emissions of nitrous oxide

Agricultural soils and manure management are the dominant sources (about 60-90%) of emissions of N_2O in the Nordic countries (Antman et al., 2015). Efficient use of N will contribute to overall lower N application, which should generally yield lower N_2O-emissions (Bakken and Frostegård, 2017). Table 4 provides an overview of measures to reduce emissions of N_2O from the agricultural sector in the Nordic countries.

Table 4. Overview of measures to reduce emissions of nitrous oxide (N_2O) from agriculture in the Nordic countries. Updated from Hellsten et al. (2017).

Measure	Implementation
Effective use of manure and fertilizers Efficient N use will contribute to overall lower N application and hence lower emissions of N_2O. The amount of manure should be adjusted to the need of crops. In a Nordic climate, spring application is more efficient than autumn application, but application on warm, wet soils should be avoided.	See Table 2.
Avoid porous crusts, e.g. straw Porous crusts during storage of slurry, urine and digested manure may increase the risk of emissions of N_2O (using e.g. a plastic sheet is better). However, it may depend on situation and sometimes a crust is better than no crust. Covering solid manure heaps with a plastic sheet may reduce emissions of N_2O (Hansen et al., 2006).	See Table 2.
Rapid incorporation of manure after application Likely reduces losses of N_2O. Some methods for low ammonia emission application of manure may increase emissions of N_2O, but from a holistic perspective it is still advantageous regarding greenhouse gases.	See Table 2 and Table 3.
Digestion of manure Anaerobic digestion does not result in significant N_2O production, while aerobic digestion (either as compost or as aerated slurries), will emit large amounts of N_2O. However, both potentially reduce N_2O emissions after application to soil, because digestion makes the nutrients more easily accessible for the plants. Emissions of N_2O can be reduced/avoided by applying a long digestion process, cooling the digested manure or collecting the gas.	See Table 5.
Catch crops Reduce nutrient leaching, and likely also reduces losses of N_2O (but may increase the use of pesticides).	See Table 5.
Spring tillage Spring tillage likely reduces losses of N_2O (as long as the soil is not compacted).	See Table 5.
Use of nitrification inhibitors Inhibiting nitrification of ammonium fertilizer will significantly reduce N_2O emissions. Potentially reduces emissions by 35% (Ruser et al., 2015).	In the Nordic countries, there are no subsidies and very limited use of nitrification inhibitors, though some use in Denmark. The limited use of urea and liquid N products is one of the reasons for the interest in inhibitors in Sweden.

2.3 Measures to reduce nitrate leaching

Agricultural producers in the Nordic countries can get support for a number of measures to reduce nitrate leaching within the Rural Development Programs (RDP). Bechmann et al. (2016a) concluded that the agricultural mitigation measures targeting water management for agriculture in the Nordic countries have many similarities, despite natural and institutional differences between the countries. Table 5 provides an overview of measures to reduce nitrate leaching and level of implementation in the Nordic countries.

Table 5. Overview of measures and costs (per kg N reduced to the sea) to reduce nitrate leaching in the Nordic countries. Updated from Hellsten et al. (2017).

Measure	Denmark	Sweden	Finland	Norway
Manure management Effective utilization of manure and slurry as well as closed periods of spreading is important to reduce nitrate leaching. Maximum N manure limits are set within the Nitrates Directive, see Table 6. **Cost:** 42-840 € (Agrifood, 2015).	Advisory services and education regarding storage and spreading of manure are available in each country. Denmark has stronger restrictions in N application compared with Sweden, Norway and Finland (see Table 2).			
Digestion of manure Makes the nutrients more easily accessible for the plants and therefore less nitrogen is leached to the aquatic environment (Sørensen and Duus Børgesen, 2015). However, during digestion of manure, ammonium and pH increases, which increases the risk of ammonia emissions during storage and spreading (Möller et al., 2008). Therefore it is important to cover the stores and use low emission applicators of digested manure.	About 7% of manure was digested in 2012. In 2020 the assumption is that this number will have increased to 19% (Jensen et al., 2015).	Biogas plants are being developed with support for investment. 41 manure digestion farm plants existed in Sweden in 2016 (SEA, 2017).	6% of pig slurry and about 1% of other manure is currently digested (Luostarinen et al., 2018). Investment support can be applied for construction of a biogas plant.	Subsidies are provided to manure used for biogas.
Catch crops A catch crop is grown between two main crops and takes up the plant nutrients left in the soil after harvest, hence reduces leaching. **Cost:** 1-3 € (Eriksen et al., 2014)**.** If changes in the crop rotation are required the cost will be higher, 21-32 €.	Denmark has mandatory crop rotation plans e.g. requirements of 8-14% catch crop winter cover. If a farmer has a permit to expand the livestock husbandry, part of the permit can call for extra catch crops. Furthermore, Denmark has a scheme in which farmers can be subsidized for a hectare of catch crops as part of a compensation for increasing the N quotas and partly as implementation of the WFD.	Investment support (subsidies) is provided for catch crops.	Catch crops are supported and regulated within the Finnish Agri-Environmental Program.	Investment support (subsidies) is provided for catch crops.
Combined catch crops and spring tillage Reduce nutrient leaching during October to March. Spring tillage is associated with a lower risk of nutrient leaching than autumn tillage, but may increase the use of pesticides during the growing season. **Cost:** 10 € (SLU, 2010).	Tillage is banned in autumn before spring sown crops the following spring, unless you are sowing a winter crop or a catch crop. Tillage is prohibited after harvest and is permitted again from Feb 1 (on sandy soils) and from Oct 1 (on sandy clay and organic soil), and from Nov 1 (on clay soil).	Investment support is currently provided both for catch crops and spring tillage.	Both catch crops and reduced tillage are supported within the current Agri-Environment Program.	Subsidies are given for catch crops in combination with spring tillage.
Wetlands Re-establishment and construction of wetlands may act as N (and P) traps. **Cost:** 4 € (Eriksen et al., 2014), 5-8 € (SLU, 2010).	Investment support is provided for the construction of wetlands in Denmark, Finland, Norway and Sweden,			
	Denmark plans to build many constructed wetlands to reduce leaching.	In Sweden, investment support is provided for the maintenance of wetlands.		In Finland, investment support is provided for the maintenance of wetlands.
Controlled drainage The farmer controls the runoff from arable land by adjusting the ground water level using installed wells. Hence N leaching to surface water can be reduced.		Investment support is provided to controlled drainage in Sweden and Finland. In Finland, controlled drainage has been seen as a good measure to reduce both leaching and emissions of N_2O from peat soils while Denmark has had mixed experiences regarding the effectiveness of controlled drainage. This is likely due to the different soil conditions that apply.		
Extensive ley/cultivated grasslands Contribute to reduced plant nutrient losses and erosion.	Investment support is provided to low N grasslands in environmentally sensitive areas.	Farmers in areas dominated by cereal production can receive compensation for areas with perennial grassland within the RDP as a way to reduce N leaching and increase biodiversity.	Environmental management grasslands are part of the Agri-Environmental Program.	

Manure management, i.e. effective storage and utilization of organic fertilizer, is important to reduce nitrate leaching. For instance, optimized N fertilization contributes to overall lower N application, which will reduce N leaching. Timing and weather conditions during application is also important. Fertilizing with manure in the autumn mainly means that a large portion of the N can be lost through leaching, rather than fertilizing the crop, unless catch crops are present. Catch crops (typically *Lolium*, other grass species, or fodder radish) can reduce excess leaching after autumn fertilization, however, they must be sown sufficiently early and require relatively mild weather conditions in order to develop properly. In a Nordic climate such conditions are not present every year and therefore the effect of catch crops is highly variable between years. Restricting application periods is a more effective approach to prevent N from leaching, particularly in a wet climate.

In Denmark, strict regulations of the use of N fertilizers have contributed to reduced N leaching from agricultural areas (Windolf et al., 2012). Denmark has set minimum standard utilization demands for manure in the guidance documents for fertilizer management plans (EPA, 2017). In addition to regulation for use of N fertilizer, catch crops and wetlands are some of the most cost effective measures to reduce nitrate leaching in Denmark (Eriksen et al., 2014).

In Norway, there is a potential in some areas for more efficient use of N fertilizers at a low cost, resulting in a lower N surplus (Bechmann et al., 2014). Suggested measures include: i) improved nutrient rates based on average yield instead of highest expected yield as a basis for N application, ii) split N application, iii) precision N application and iv) improved efficiency in use of manure (Bechmann et al., 2016b). However, no legal regulations for these measures exist.

Also in Sweden, manure application technique and timing of manure spreading are important means recommended to reduce N leaching (Andersen et al., 2014). By the end of the 1990's, legislation was introduced on when, and how fast, manure should be incorporated into the soil. About 24% of surface spread manure (both solid and liquid) is directly incorporated into the soil (Statistics Sweden, 2014). Direct incorporation may increase N leaching, since there will be more N available for leaching, but it reduces P loss in surface runoff and also ammonia emissions, which is the main purpose. Reduced losses by immediate incorporation should be coupled with lower application rates of manure and mineral fertilizers. Reduced tillage may increase leaching via micro pores and has been used as a measure to reduce N leaching in Sweden (Andersen et al., 2014). Farmers in Sweden can apply for support within the Rural Development Program for postponing plowing from autumn to spring. Subsidies to encourage precision farming, using N-sensor techniques to apply optimum levels of nutrients from mineral fertilizers are applied in some counties in Sweden.

In Finland, the Nitrates Directive is implemented in the whole country, see Table 6. It sets maximum annual application rates of soluble N (kg ha^{-1}) for various crops. From 1st September the amount of soluble N in farm animal manure and organic fertilizer products may not exceed 35 kg ha^{-1}. The Nitrates Directive also regulates the timing and type of spreading. The voluntary Agri-Environment Program, which has been adopted by the majority of farmers, sets slightly lower application maximums than the Nitrates Directive. Moreover, the voluntary program includes subsidies for crop cover (reduced tillage, stubble, grass and winter crops) during autumn and winter that contribute to lower N losses to ground and surface waters. Recently, incentives to plant cover crops were applied in some areas with high potential to reduce N leaching (Valkama et al., 2015).

Table 6. Summary of the most important EU Directives regarding nitrogen and agriculture.

NECD	National Emissions Ceilings Directive	Sets emission targets (e.g. for ammonia) until 2020 and 2030.
ND	Nitrates Directive	Sets maximum N manure limits in nitrate vulnerable zones, for the NO_3 concentration to be below WHO standards.
WFD	Water Framework Directive	Sets standards for N abatement in watersheds, to meet defined water qualities in streams, lakes and coastal waters, especially critical for regions that border the sea.
IED	Industrial Emissions Directive	Regulates large pig and poultry farms (>40 000 places for poultry, >2 000 places for production pigs (over 30 kg), or >750 places for sows). Best available techniques (BAT) should be applied to reduce emissions, with guidance provided by published BAT Reference documents (BREFs)

3. Progress in implementing nitrogen management actions in the Nordic countries

The dominant policy instruments to reduce N losses from agriculture in the Nordic countries today consist of rules and regulations, marked-based regulation, subsidies or information and voluntary action. Bechmann et al. (2016a) noted that, although there are many similarities regarding agricultural mitigation measures implemented in the four countries, there are large differences between the instruments used in the agricultural policy. In Denmark most of the measures have been legislated, but with a recent shift towards a more geographically differentiated and voluntary framework (Dalgaard et al., 2014). In Finland and Norway, regionally adapted incentive-based policies are used and agricultural environmental policies tend to have focused more on the problem of P, especially in Norway. In Norway, the legislation on manure management, the Regional Environmental Program and the subsidies for environmental investments, successfully motivates farmers to implement measures, mainly aimed at minimizing P losses. The Finnish "Agri-Environment Program" payment system has succeeded in enlisting 90% of farmers to the program. It has reduced soil P status and thereby the risk of P losses from fields while increased crop cover during winter has also reduced N leaching. The voluntary Swedish advisory program "Focus on Nutrients", running since 2001, has helped reduce N leaching and decreasing N transport from agricultural land to rivers (Fölster et al., 2012; Agrifood, 2015). The campaign focuses on increasing nutrient management efficiency by increasing awareness and knowledge using techniques described above. The core of the information campaign is education and individual on-farm advisory visits. "Focus on Nutrients" also provides information on a webpage (www.greppa.nu).

In the other Nordic countries, short-lived agri-environmental projects have targeted geographical areas. For example, in south-west Finland, two agri-environmental projects TEHO (2008-2011) and TEHO Plus (2011-2013) (Launto-Tiuttu et al., 2014), as well as in southern Finland JÄRKI (2009-2013 and 2014-2018) have been running (www.jarki.fi). In Norway similar approaches have been implemented for specific areas, e.g. the lake Vansjø and Skas-Heigre catchments, where contracts with farmers on environmental behavior were introduced together with farm visits. However, the main focus was on P rather than N. In Norway, the webpage "Tiltaksveilederen" (www.nibio.no/tiltak) present information on mitigation measures to reduce nutrient losses from agriculture. In Denmark, the new watershed advisory scheme and the work with water councils (Graversgaard et al., 2016) are other examples of information campaigns. Similar actions were also undertaken in Denmark in the 1990's in campains called "Gylle er guld" ("manure is money").

3.1 Ammonia emissions

Ammonia emissions in the Nordic countries (Figure 1) mainly originate from agriculture (about 94% in Denmark (Nielsen et al., 2018), 92% in Norway (Statistics Norway, 2018), 91% in Finland (MAF, 2018) and 88% in Sweden (SEPA, 2018).

Denmark has had the largest reduction in emissions of ammonia by about 40% between 1990 and 2013 (Nielsen et al., 2018). During the same time period, the reduction in Sweden was 12%, and in Finland 11% (SEPA, 2018; MAF, 2018). In Norway, ammonia emissions have even increased by 6% since 1990 (Statistics Norway, 2018). In Sweden, the reduction in ammonia emissions is mainly a result of decreased livestock numbers, reduced use of inorganic fertilizers and a more effective agricultural production (SEPA, 2018). At the same time, meat consumption and meat import has increased (SBA, 2013b), hence in principle the ammonia emissions (and also other related nitrogen impacts such as contamination of water) have been transferred elsewhere. After the 23 year reduction in ammonia emissions in Denmark, emissions are no longer decreasing (since 2013, see Figure 1). Furthermore, projections, based on assumptions on future policies and market development, indicate relatively small emission reductions in the coming years (Nielsen et al., 2018). It is therefore clear that additional action and incentives to reduce ammonia emissions are necessary to stimulate further reductions.

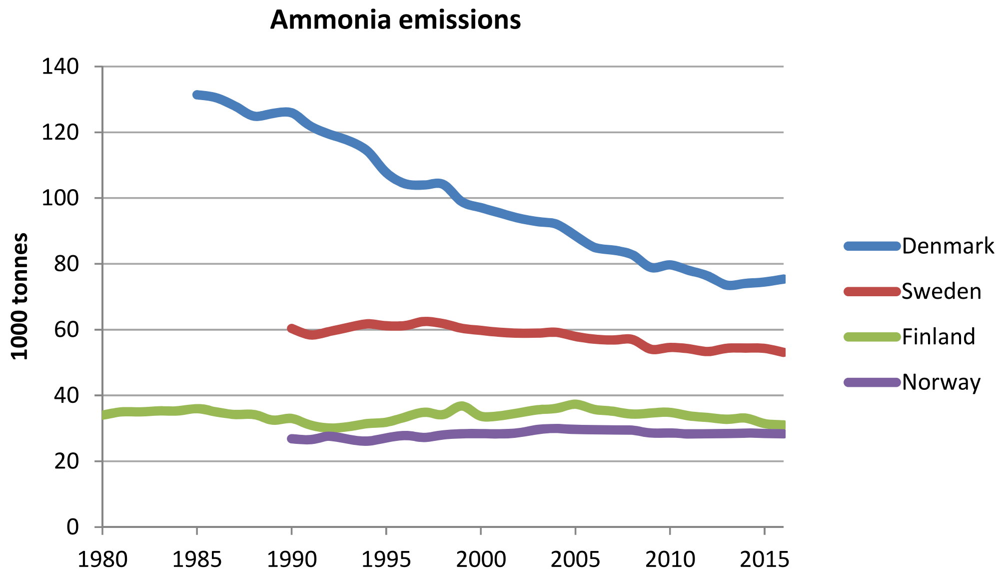

Figure 1. Ammonia emissions (thousand tonnes) in Denmark, Sweden, Finland and Norway during 1980-2016. Source: Nielsen et al. (2018); MAF (2018); SEPA (2018); Statistics Norway (2018).

3.2 Nitrogen deposition

The nitrogen deposition in the Nordic countries has been reduced by about 25-30% since the 1980´s (Ellermann et al., 2013; Ferm et al., submitted; Karlsson et al., 2018). Nitrogen deposition derives both from reduced nitrogen (NH$_{X,}$) i.e. mainly ammonia emissions, and from oxidized nitrogen (NO$_X$) i.e. from fossil fuel combustion. Agricultural N policies have mainly affected ammonia-based emissions (and depositions), hence only a small proportion of the total N depositions. The remaining part, (primarily NO_X-emissions) derives mainly from road transport. In the EU, emissions of NOx are about twice as large as emissions of ammonia (EEA, 2018).

In Denmark, both measurements and model calculations show a decrease in N deposition of about 25% from 1989 to 2009 (Ellermann et al., 2013). N deposition has also decreased in Sweden. A reconstruction of old measuring series in Sweden since 1955 indicates that the wet deposition of N (both nitrate and ammonium N) culminated in the mid-1980's (Ferm et al., submitted). Since then, the wet depositions of both ammonium and nitrate have decreased by about 30%.

The measured total N deposition (nitrate and ammonium N) to coniferous forests in Sweden has decreased by 27% from 2001-2016 (Karlsson et al., 2018). During this time period, NH_3-emissions in Sweden have been reduced by about 10%, while NO_X-emissions have been reduced by about 36%, so the majority of the N-deposition reduction is expected to be derived from NO_X. During the same time period, Finland has not shown the same decreasing trend in N deposition (Vuorenmaa et al., 2018). The regional scale annual total N deposition in Norway is estimated to have been in the order of 177 ktonnes during 1978-1982, and was reduced to about 144 ktonnes in the period 2012-2016, a reduction of about 25% over nearly 35 years. The corresponding trend in reduced N deposition was from about 93 thousand ktonnes to 73 thousand ktonnes (22% reduction) (Aas et al., 2017).

3.3 Nitrate leaching to the aquatic environment

Denmark has had the highest reductions when it comes to N leaching to the sea. During the past 25 years, average N-surplus in Danish agriculture has been reduced from almost 200 kg N ha^{-1} yr^{-1} in the beginning of the 1990's to about 80 kg N ha^{-1} yr^{-1} (See Figure 2). As a result, the N load to marine waters has been reduced by 50% and the previously increasing trend of N content in groundwater now shows a decreasing trend (Hansen et al., 2011; Windolf et al., 2012). This reduction has mainly been accomplished by restricting use of N fertilizers which give farmers incentive to improve N use efficiency. Since the mid-1980's, a series of policy action plans to mitigate losses of N have been implemented in Denmark. However, despite large reductions in nitrate leaching, the targets set for the Water Framework Directive (see Table 6) are sometimes exceeded, hence further reductions are still needed.

In Norway, the estimated losses of N from agricultural areas to marine waters increased by 11% from 1990 to 2011 (Selvik et al., 2012). In Norway, the main focus has been on mitigation measures reducing P losses, for instance measures targeted to erosion, e.g. reduced soil tillage. P is closely related to erosion and therefore these measures will affect P.

In Sweden, inorganic N leaching from agricultural land has decreased since the 1980's. Monitoring stream water in 65 small catchments dominated by agriculture, show that inorganic N leaching from agricultural land has decreased between 35-60% during a 20-year period (1991-2010) in southern and central Sweden (Fölster et al., 2012). The leaching reductions were greatest in those regions where the most extensive N mitigation measures had been implemented, i.e. the introduction of catch crops, increased areas of grassland, improved manure management, more winter cereals and less spring cereals.

In Finland, the N load from agriculture to waters has been calculated from long term measurements, showing only a marginal decrease in recent years, despite considerable reductions in fertilizer use and N field balances (Rankinen et al., 2016). The N balance has been reduced by 40%, from 78.7 kg ha^{-1} (1995) to 47.4 kg ha^{-1} (2016) (Luke, 2018). These values represent average values for the whole country, hence in more intensive areas in south-western Finland in drainage basins of the Archipelago Sea the N load from agricultural land is higher than this.

3.4 N surplus

The gross N balance, i.e. the potential surplus of N on agricultural land, is a means to assess nutrient management and efficiency in agriculture. It is estimated by calculating the balance between N inputs (fertilizers and manure, atmospheric deposition, biological fixation and seeds and planting material) and N outputs (fodder/grazing and crop harvest) from the agricultural system per hectare of agricultural land. A surplus indicates potential environmental problems, while a deficit may indicate a decline in soil nutrient status.

Denmark and Norway currently have a higher N surplus compared with Sweden and Finland, see Figure 2. Although Norway has the highest N surplus per ha, the agricultural area in Norway is about 1/3 of that of Denmark and Sweden and almost 1/2 that of Finland, therefore the total N surplus (from the whole country) is about twice as big in Denmark compared with the other Nordic countries, see Table 1.

N surplus has decreased in Denmark, Finland and Sweden since 1990, particularly in Denmark (by more than 50%). Despite large reduction in N surplus, Denmark has matched increasing productivity of other European countries (Kijek et al., 2015), hence demonstrating that there was room to improve environmental quality without sacrificing productivity.

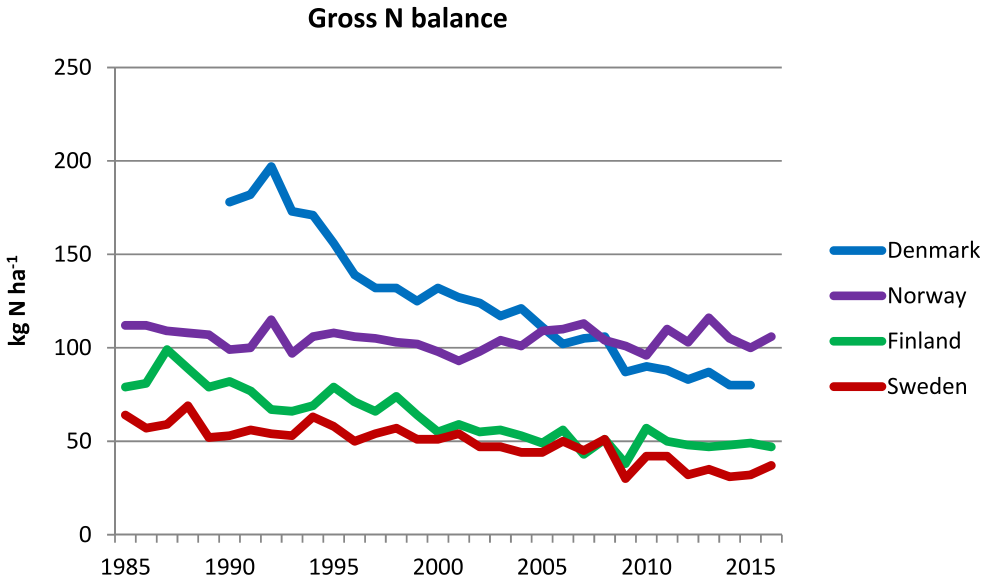

Figure 2. Gross N balance (kg N per ha of agricultural area), 1985-2016. Source: Eurostat (2018).

4. Nitrogen challenges

4.1 Compliance with the NEC-directive

Through the EU National Emissions Ceilings (NEC) Directive, Denmark has committed to reduce ammonia emissions by 24%, Finland by 20% and Sweden by 17% until 2030 (compared with the base year 2005) (EEB, 2017), see Table 7. Norway is not committed to the NEC-Directive and has had the smallest emission reduction among the Nordic countries, 4% since 2005 and even an increase of 6% since 1990, see Table 7.

Table 7. Ammonia emissions (ktonnes) 1990, 2005 and 2016 (based on data in Figure 1) and predicted emissions in 2030 if the NEC-target for 2020 and 2030 is to be fulfilled. For 2016 also the emission change from 1990 and 2005 is shown.

	1990	**2005**	**2016**	change since 1990 / 2005	**2020* NEC-target**	change since 2005	**2030* NEC-target**	change since 2005
Denmark	126	89	75	-40% / -15%	59	-33%	67	-24%
Sweden	60	58	53	-12% / -8%	49	-15%	48	-17%
Finland	35	35	31	-11% / -11%	28	-20%	28	-20%
Norway	27	30	28	+6% / -4%	-	-	-	-

*The NEC-target is stated as a reduction percentage from year 2005. Here we provide the emission based on the emission value for year 2005 from Nielsen et al. (2018), SEPA (2018), MAF (2018) and Statistics Norway (2018).

In Denmark, emission reductions relative to 2005 are predicted to reach 18% by 2020 and 20% by 2030 (Nielsen et al., 2018). Hence, target reductions (-24%) will not be reached until 2030. The decreasing emissions are primarily expected from manure management, especially from the pig industry, mainly due to implementation of emission reducing technology in livestock housing systems. This is, however, partly counteracted by an expected increase in the use of mineral fertilizers. Interestingly, the largest absolute decrease in ammonia emissions in Denmark is predicted from bioenergy based local district heating systems and wood or pellets based heating systems in residential homes.

In Finland, agricultural ammonia emissions are expected to be about 29.6 ktonnes in 2020 and 27.5 ktonnes in 2030. Hence according to the projections, the NECD-target for 2030 will be achieved.

In Sweden, ammonia emissions have been reduced by 8% since 2005, which is only half way to the reduction target for 2030 (17%). A gradual transition from systems with solid manure to slurry systems, with 62% slurry systems for cattle and pigs (Statistics Sweden, 2017), has resulted in reduced ammonia losses. This trend is expected to continue. However, unless livestock numbers are reduced, even further measures are needed, e.g. lowering the crude protein in fodder further or use more efficient covers for slurry compared with natural crusts. This would require increased advice or stricter legislation regarding feeding and housing conditions. In Sweden, feeding is increasingly adapted to the individual animal with the help of data collection with sensors, a trend that is likely to cut emissions of ammonia in the future.

In Norway, manure spreading accounted for 86% of the ammonia emissions from the agricultural sector, whereas mineral fertilizer accounted for 9% (Bye et al., 2017). In Sweden, by comparison, manure spreading only accounts for 33% of the agricultural emission, whereas mineral fertilizers are at about the same level as in Norway (10%). The dominating method for manure spreading in Norway is broadcast spreading (see Table 3), which contributes to the high emissions of ammonia. This clearly shows that changing into low emission spreading techniques have a potential to cut emissions. Since 1990, ammonia-emissions from manure in Norway have increased by 14% (Bye et al., 2017). Ammonia-treatment of straw has decreased causing less ammonia emissions from this source (Bye et al., 2017).

5. Policies to reduce nitrogen losses from agriculture – The way forward

The pressure to reduce N losses from agriculture has been increasing in the Nordic countries. Actions related to the WFD, the Nitrates Directive and the designated nitrate vulnerable zones (EC, 2018) have a high priority in all four countries. The WFD is primarily target (output) oriented, toward the effect in the water environment, while the Nitrates Directive is primarily input oriented, limiting the use of manure in nitrate vulnerable zones, see Table 6. Furthermore, Denmark, Sweden and Finland are part of HELCOM (the governing body of the Convention on the Protection of the Marine Environment of the Baltic Sea Area), where measures to prevent N leaching have very high priority, because most of the countries have reduction conditions set in the Baltic Sea Action Plan.

Failure to comply with the NEC-directive and occasional exceedances of targets set for the WFD show that clearly, there is a need for further reductions in the Nordic countries, and further focus on working with farmers and other relevant actors to reduce N emissions and increase N efficiencies are needed throughout the whole production chain.

Since the countries have different priorities and strategies regarding agricultural N flows and mitigation measures, the way forward is different. Denmark has achieved substantial reductions of N input, while at the same time maintaining and even increasing agricultural production value, in particular in relation to a more and more N efficient livestock production. Between 2007 and 2013 Denmark increased its agricultural total factor productivity by 3.2%, Finland by 1.9% and Sweden by 0.2% compared with 0.1% growth as an average for the EU countries (Kijek et al., 2015).

In Denmark, initial agricultural measures were successful and effective because they were cost effective and in many cases beneficial for the farmer. Sweden, Norway and Finland may not yet have picked all the low hanging fruit, for instance when it comes to low ammonia application techniques, and therefore have a potential to reduce more N losses from agriculture at a reasonable cost. Today there are many measures available, but these measures are not always applied, and the reasons for not applying these measures need to be identified and further investigated. Wreford et al. (2017) have identified two main approaches to remove barriers:

1) Revision of agricultural policies that prevent the objectives of the aim (e.g. a more N efficient agriculture).

2) Introduction of targeted initiatives to remove the most important barriers.

Agricultural producers may be facing long term investment costs (maybe > 20 years) from implementing abatement measures, hence availability of funds could help to mobilize change and overcome economic barriers. In Norway for instance, voluntary measures consist of investment support and subsidies, to establish sedimentation ponds and wetlands.

5.1 More stringent regulations, or not?

Agricultural abatement measures should not be too expensive to the farmers, and should ideally even pay for themselves, e.g. through advisory efforts that increase the utilization of livestock manure and thereby obtain a reduction in the cost of mineral N fertilizer due to savings of N within the farming system. For instance, improved nutrient management planning, accounting for plant available of N in manure and based on average yield instead of maximum yield on a field, could be an easy way to reduce N application with low cost for agricultural producers (e.g. Bechmann et al., 2016b). It is important to communicate and promote existing techniques to agricultural producers who have not yet adopted them.

Farmers and their organizations generally prefer voluntary approaches compared with regulations. Some farmers may be interested in implementing measures to reduce environmental problems, even if it is costly. Hence providing information and knowledge through advisory efforts is important. However, other farmers may be reluctant to change from traditional practices and voluntary actions may result in very slow change.

Important success criteria for changed farming behavior from ”Focus on Nutrients” in Sweden have been voluntary measures and repeated farm visits, relating to how measures will influence farm economy (positively or negatively) and feedback to agricultural producers regarding the environmental progress (e.g. through the press) to make the farmers proud of their achievements.

Sutton et al. (2018) concluded that a solely voluntary and economic approach is unlikely to promote the necessary changes needed to meet the ammonia emissions ceilings in the NEC Directive for 2020, and that additional regulation will be necessary. For instance, Norway has focused on P more than N, hence there may be a need to adjust the regulatory framework to reduce N losses from agriculture further. For instance, Norway needs to have more focus on the use of N fertilizer, i.e. a balanced N application.

The only country to achieve major emissions reduction among the Nordic countries, Denmark, had achieved it by a regulatory approach. However, it is unlikely that other countries with significantly lower animal density could reduce losses to the same extent solely by means of legislation. In Denmark, regulations have been an increased burden for farmers, and recently there has been a shift towards a more voluntary framework.

Engaging with relevant stakeholders, such as farmer’s associations, to assess required changes and finding suitable solutions and mitigation measures can be useful to prepare the way for mandatory measures. “Focus on Nutrients” in Sweden has been a good framework to communicate knowledge and information and may therefore already have built a good basis for further development and acceptance of mandatory measures among Swedish farmers. The Swedish Board of Agriculture provide some examples of potential mandatory measures in Sweden, e.g. that the current manure management regulations could be extended also to include digested manure, more efficient covers and an expansion of the geographical area for regulations on manure application (SBA, 2010). Another example could be to further regulate urea and slurry application in Sweden. On the other hand, OECD (2018) recommend that Sweden should reduce administrative costs by simplifying agricultural regulations (regarding the environment, animal and crop health, and animal welfare) that go beyond EU regulations. This message indicates that, from a European perspective, the legislative burden is already high and should be coordinated and simplified for the convenience of farmers.

In all Nordic countries, there is a trend towards larger farms that may be more profitable, while small farms are gradually disappearing. Currently large pig and poultry farms are regulated through the Industrial Emissions Directive (IE Directive), applying Best Available Techniques (BAT) to reduce emissions, with guidance provided by published BAT Reference documents (BREFs) (Santonja et al., 2017). If current trends are extrapolated into the future, it is likely that most poultry and pork will be produced on IED-farms in the Nordic countries. Large cattle farms are not included in this regulation. Considering that there is an increasing number of industrial-scale cattle farms, Sutton et al. (2018) highlighted the opportunity to include also cattle farms in the regulations to follow BAT.

Another trend regarding agricultural policies in the Nordic countries is that they are likely to move more towards geographically targeted policies. Sweden and Norway already have stricter rules and regulations in some parts of the country (in nitrate vulnerable areas according to the Nitrates Directive), hence has adapted regionally targeted policies. Denmark plans to bring this concept of region specific solutions even further. A new agricultural legislative package will target measures according to site specific characteristics, e.g. based on targets for N loading to specified inshore water. From August 2019, Danish farmers may therefore have different management restrictions depending on e.g. soil type and in which water catchment their farm is located (EPA, 2017). Reducing environmental impact in the most sensitive areas is important. However, Sutton et al. (2018) noted that additional action in “hot spot” areas to maximize the environmental benefits typically offer smaller contribution to total emission reduction.

5.2 More efficient use of manure and mineral fertilizers

Norway, having the highest average N-surplus among the Nordic countries (see Figure 2), indicates a need to have more focus on the use of N fertilizer, i.e. a balanced application. Norway has not regulated fertilizer N rates (except for the maximum amount of livestock manure to be applied, 170 kg N ha^{-1}, in the nitrate vulnerable zone). In Sweden, there is currently an exciting development in precision agriculture, using satellite images together with vegetation maps to adjust N rates to crop needs.

McCrackin et al. (2018) concluded that manure is often not being used efficiently in the Baltic region, particularly in countries with a high livestock density. However in Denmark, the Nitrates Directive limits the amount of pig manure-N that can be applied to arable land. Less than half of Danish pig farms have enough agricultural land to comply with these limits, and therefore, farms must rent additional land or have other farms take care of the excess pig manure (Willems et al., 2016). Redistribution of manure from animal-dense areas to crop-producing areas may therefore be important to increase manure use efficiency. In some parts of Finland for instance, manure is spread without consideration to efficacy, i.e. disposed rather than used. If manure is used more effectively, it can (partly) substitute costly and energy-demanding mineral fertilizers. However, transporting manure is energy intensive and may damage roads. Furthermore, the financial cost of moving manure is very much a concern and the price is dependent on the distance of transportation. Birkmose et al. (2015) has estimated the transportation cost of pig manure in Denmark at 1.3 Euro per ton (1 km), 1.9 Euro per ton (5 km) and 2.4 Euro per ton (10 km).

N-taxation may be a means to influence the supply of reactive N into the agricultural system. Sweden and Norway have had a tax on mineral fertilizers and recently a re-introduction of the tax has been discussed in both countries, see Table 8. The main reason for the re-introduction is the lack of effective policy instruments to reduce the supply of N through fertilization.

Table 8. Comparison of N taxation on mineral fertilizers in Denmark, Sweden, Finland and Norway.

Denmark	Sweden	Finland	Norway
N taxation is not implemented in Denmark, but there is a pesticide tax as well as a tax on P in fodder.	In Sweden, a tax on mineral N fertilizers was introduced in 1984 to reduce N pollution, but it was abolished in 2009 because it was considered to be ineffective. A reintroduction of the tax has been discussed in recent years.	In Finland, there has been no tax for fertilizer nutrients after joining the EU in 1995. Before that, a P tax in the beginning of the 1990's was able to efficiently reduce P fertilization.	Norway had a tax on mineral fertilizers (1988-2000). A reintroduction of the tax of 0.3 € per kg of N has recently been suggested to reduce emissions of N_2O (NOU, 2015:15).

In Sweden, the previous N tax only reduced emissions of N_2O by about 2% because the Swedish N efficiency was already high (KI, 2014). The N tax was abolished because it was considered to have little impact on the use of fertilizers, but also to increase the competiveness of Swedish agriculture. When the N-tax in Sweden was abolished, the use of mineral fertilizers did not increase, probably because the price was unchanged due to a general price increase on N fertilizer on the world market (KI, 2014). Also in Norway, the effectiveness of the tax compared with other measures has been questioned (Bechmann et al., 2016b).

5.3 New innovation

Denmark has been a pioneer among the Nordic countries when it comes to utilize and develop knowledge and techniques to increase the utilization of N in manure, e.g. trailing hose slurry application techniques, acidification of slurry and phase feeding of livestock. In earlier versions of the UNECE Ammonia Guidance Document, slurry acidification was not considered a recommended method. However, considering the success across Denmark this recommendation was later revised. Today there are initiatives to identify possibilities and obstacles to implement slurry acidification in the Baltic Sea Region (Rodhe et al., 2018).

This highlights the importance of investment to develop new technological innovations of more efficient measures. Methods to improve precision farming, i.e. using satellite images and sensors to adapt the N input to the soil, are interesting areas for research. Furthermore, more research is needed regarding novel approaches to reduce N_2O emissions from agricultural soils, e.g. by increasing soil pH. Another example refers to technique development to improve the efficiency of air scrubbers (to reduce ammonia emissions from animal housing) so that they can be more widely used in the Nordic countries.

Modern technology to increase the utilisation of N in manure is important, but is not the only solution to the problem. Overall good farming, i.e. precise farming, reduced soil compaction, pest control etc. with modern technology is also important in order to produce more with less. In this way higher yields with lower nitrogen losses and net greenhouse gas emissions can be obtained.

5.4 Integrated policy approaches

Due to the complexity of the N cycle and co-benefits and trade-offs with other pollutants and effects, we recommend a holistic approach that covers the full N cycle to tackle the problem of N losses from Nordic agriculture. Recently the German government has highlighted the need for integrated policy approaches to N reduction to enable a holistic view of the total reactive N balance, beyond sector specific reduction measures (GME, 2017). Ammonia experts have concluded that (expressed as kg of N), abatement of ammonia emissions can be rather cheap, compared with further abatement of NO_x (Reis et al., 2015). Hence, technical measures within the agricultural sector are more cost effective compared with N reductions within other sectors already subject to more stringent regulations.

In the Nordic countries, as well as in the rest of the world, increasing concern about climate change has resulted in policy actions to combat emissions of greenhouse gases. It is likely that future agricultural policies in the Nordic countries will include agricultural climate change policies, which will probably also influence N management. In Denmark for instance, the overall Danish Climate Policy Plan aims to achieve a 40% reduction in GHG emissions by 2020 compared with 1990 levels (The Danish Government, 2013). A holistic N policy approach can offer the opportunity to also incorporate reduction of methane emission from agriculture (e.g. Hellstedt at al., 2014, Dalgaard et al., 2015).

This study mainly focuses on technical measures to reduce N losses from agriculture. However, we noted that technical measures may not be enough to reach the pollution targets, hence also system change measures, such as reduction of food waste, increasing the overall efficiency in the food chain, or promotion of consumption patterns with lower N footprints (e.g. Karlsson et al., 2017; Ocké et al., 2017; Westhoek et al., 2015), may be needed. Leip et al. (2015) concluded that a combination of technological measures to reduce N losses from agriculture, improved food choices and reduced food waste is necessary in order to make significant progress in mitigating environmental effects from N.

5.5 Recommendations on the way forward in the Nordic countries

The Nordic Governments should continue to consult relevant stakeholders, researchers and farmer's associations on which measures to prioritize for two reasons:

- Finding the most efficient and feasible measures to implement, and
- having the support of the farmer's associations facilitates the process of implementing mandatory measures.

It is equally important to influence attitudes in a general sense and in a specific sense like local hotspots such as water quality. Before designing and implementing new agricultural policy, the Nordic Governments should:

- Firstly, identify potential barriers to the implementation, and
- secondly, identify ways to tackle the barriers, e.g. through increased awareness and knowledge among the farmers regarding the effect of the mitigation measure, or through the availability of funds (subsidies).

It is important to pick low hanging fruits through use of the most cost effective mitigation measures. First of all, N application rate and its timing should be in accordance with the plant need and carrying capacity of environmental recipients. Also, the choice of application technology can further reduce the risk of N losses into air and waters. This may require more region-specific solutions and knowledge-based support with tailored information in combination with further targeted subsidies or regulations.

The effect of N-taxation on mineral fertilizers should be further assessed to better understand the effectiveness of a new N-taxation. Furthermore, investing in the development of new technological innovations is important in order to develop the next generation of efficient mitigation techniques.

System change measures, e.g. reduced food waste, improved food choices and efficiency in the food chain would further contribute to reducing environmental effects from N. Finally, there is a need to emphasize holistic approaches across the N cycle and also links to measures for climate change.

6. Conclusions

The four Nordic countries are at different levels regarding agricultural N flows and mitigation measures, and therefore they are facing different challenges and barriers. In Norway, focus has been more on P than N. In Norway and Finland subsidies are widely used, whereas in Denmark regulations have, until now, been the main form. In Sweden voluntary actions and information campaigns are important.

It is evident that commitment to the WFD, Nitrates directive and the NEC Directive has had effect. However, to reach the environmental goals by 2020 and 2030, different countries will have to take different routes based on their actions in the past. A solely voluntary and economic approach may not promote the necessary changes needed, hence also the regulatory framework may need to be adjusted in order to reduce N losses from agriculture further.

Acknowledgements

This work was supported by the Environment and Economy Group (MEG) at the Nordic Council of Ministers (NCM). The manuscript was also supported from the SIVL foundation from IVL Swedish Environmental Research Institute.

Thank you to the Danish Innovation fund for sponsoring the www.dNmark.org Nitrogen Research Alliance, to Aarhus University and the Ministry of Environment and Food of Denmark for support to the related work under the UN-ECE Task Force on Reactive Nitrogen (TFRN). Moreover, thanks to the European Union for research support, among other via the H2020 NitroPortugal Project and the FAIRWAY project on "Farm systems that produce good Water quality for drinking water supplies". Thank you to the Swedish Environmental Protection Agency for funding the Research Program SCAC, (Swedish Clean Air & Climate Research Program, www.scac.se), which has also contributed to this work.

References

Aas, W., Hjellbrekke, A.-G., Fagerli, H., and Benedictov, A. 2017. Deposition of major inorganic compounds in Norway 2012-2016, NILU report, 41/2017.

Agrifood. 2015. Östersjön mår bättre när lantbrukare Greppar Näringen, Policy Brief Nummer 2015:1.

Andersen, H.E., Blicher-Mathiesen, G., Bechmann, M., Povilaitis, A., Iital, A., Lagzdins, A., Kyllmar, K., 2014. Mitigating diffuse nitrogen losses in the Nordic-Baltic countries. Agriculture, Ecosystems and Environment 198 (2014) 127-134.

Antman, A., Brubæk, S., Hessellund Andersen, B., Lindqvist, K., Markus-Johansson, M., Sørensen, J. and Teerikangas, J. 2015. Nordic agriculture air and climate – Baseline and system analysis report, Nordic Councils of Ministers 2015, TemaNord 2015:570, ISSN 0908-6692.

Bakken, L.R. and Frostegård, Å. 2017. Sources and sinks for N_2O, can microbiologists help to mitigate N_2O emissions? Environmental Microbiology 19(12), 4801-4805.

Battye, W., Aneja, V.P. and Schlesinger, W.H. 2017. Is nitrogen the next carbon?, Earth's Future, 5, doi:10.1002/2017EF000592.Bechmann, M., Blicher-Mathiesen, G., Kyllmar, K., Iital, A., Lagzdins, A., Salo, T., 2014. Nitrogen application, balances and the effect on nitrogen concentrations in runoff from small catchments in the Nordic-Baltic countries. Agriculture, Ecosystems and Environment 198 (2014) 104-113.

Bechmann, M., Blicher-Mathiesen, G., Kyllmar, K., Iital, A., Lagzdins and A., Salo, T. 2014. Nitrogen application, balances and the effect on nitrogen concentrations in runoff from small catchments in the Nordic-Baltic countries. Agriculture, Ecosystems and Environment 198 (2014) 104-113.

Bechmann, M., Collentine, D., Gertz, F, Graversgaard, M. Hasler, B., Helin, J. Jacobsen, B., Rankinen, K and Refsgaard, K. 2016a. Water management for agriculture in the Nordic countries, NIBIO Report No. 2/2/2016.

Bechmann, M., Prestvik, A., Morken, J., Nesheim, L., Grønlund, A. 2016b. Gjødselvareforskriften – utslipp av klimagasser og nitrogen til vann; Manure regulations. NIBIO report 2(133).58p. Page 51.

Birkmose, T., Hjort-Gregersen, K. and Stefanek, K. 2013. Biomasse til biogasanlæg i Danmark – på kort og lang sigt, revideret udgave, November 2013, AgroTech [In Danish]

Birkmose, T., Hjort-Gregersen, K., Hinge, J. and Hørfarter, R. 2015. Kort lægning af hensigtsmæssig lokalisering af nye biogasanlæg i Danmark – Udpegning af områder med særlige muligheder for biogasanlæg, December 2015, SEGES & AgroTech. [In Danish]

Bittman, S., Dedina, M., Howard, C.M., Oenema, O. and Sutton, M.A. (eds) 2014. Options for ammonia mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen. Centre for Ecology & Hydrology, Edinburgh.

Bye, A.S., Aarstad, A., Løvberget, A.I., Høye, H. 2017. Jordbruk og miljø 2017. Tilstand og utvikling. Statistisk sentralbyrå rapport 2017/41. 181p. (In Norwegian).

Dalgaard, T., Hansen, B., Hasler, B., Hertel, O., Hutchings, N., Jacobsen, B.H., Jensen, L.S., Kronvang, B., Olesen, J.E., Schjørring, J.K., Kristensen, I.S., Graversgaard, M., Termansen, M. and Vejre, H. 2014. Policies for agricultural nitrogen management - trends, challenges and prospects for improved efficiency in Denmark. Environmental Research Letters, Environ. Res. Lett. 9 (2014) 115002 (16pp). http://dx.doi.org/10.1088/1748-9326/9/11/115002. Web: http://iopscience.iop.org/1748-9326/9/11/115002/article and pdf link: http://iopscience.iop.org/1748-9326/9/11/115002/pdf/1748-9326_9_11_115002.pdf.

Dalgaard, T., Olesen, J.E., Misselbrook, T., Gourley, C., Mathias, E., Heldstab, J., Baklanov, A., Cordovil, C.M. and Sutton, M. 2015. Methane and Ammonia Air Pollution – Policy Brief prepared by the UNECE Task Force on Reactive Nitrogen. May 2015. http://www.clrtap-tfrn.org/sites/clrtap-tfrn.org/files/documents/NECDAmmoniaMethane_UN-TFRN2015_0513%20combi.pdf

EC, 2018. Report from the Commission to the council and the European Parliament on the implementation of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources based on Member State reports for the period 2012–2015 {SWD(2018) 246 final}

EEA. 2018. European Union emission inventory report 1990-2016 under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP), EES Report No 6/2018, European Environment Agency.

EEB, 2017. Clearing the air – a critical guide to the new national emission ceilings directive, EEB, the European Environment Bureau.

Ellermann, T, Andersen, H.V., Bossi, R., Christensen, J.H., Løfstrøm, P., Monies, C., Grundahl, L. and Geels, C. 2013. Atmosfærisk deposition 2012 (atmospheric deposition 2012) NOVANA Scientific Report no 73 from DCE National Center for Environment and Energy Aarhus University p 85.

EPA, 2017. Overview of the Danish regulation of nutrients in agriculture & the Danish Nitrates Action Programme cf. Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC), Ministry of Environment and Food of Denmark, Environmental Protection Agency, June 2017.

Eriksen, J. (ed.), Jensen, P.N. (ed.), Jacobsen, B.H. (ed.), Thomsen, I.K., Schelde, K., Blicher-Mathiesen, G., Kronvang, B., Hansen, E.M., Jørgensen, U., Andersen, H.E., Hoffmann, C.C., Børgesen, C.D., Baattrup-Pedersen, A., Rasmussen, J.J., Olesen, J.E., Kjærgaard, C., Sørensen, P., Hasler, B., Eberhardt, J.M., Rubæk, G.H., Strandberg, M.T., Kudsk, P., Jørgensen, L.N., Petersen, S.O., Munkholm, L.J., Elsgaard, L., Martinsen, L., Møller, F., Bruhn, A., Iversen, B.V., Timmermann, K., Fossing, H., Boelt, B. & Gislum, R. 2014, Virkemidler til realisering af 2. generations vandplaner og målrettet arealregulering. [in Danish] Means for the realization of 2nd generation water plans and targeted area regulation. Report prepared by the DCE, DCA and IFRO. DCA report 52, December 2014, Aarhus University.

Erisman, J.W., Galloway, J.N., Seitzinger, S., Bleeker, A., Dise, N.B., Petrescu, A.M.R., , Leach, A.M. and de Vries, W. 2013. Consequences of human modification of the global nitrogen cecle, Phil. Trans. R. Soc. B 368

Eurostat. 2018. Gross nutrient balance, Eurostat, online data code: aei_pr_gnb (update 04-05-2018) Accessed 12th of June, 2018. http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do

Ferm, M., Granat, L., Engardt, M., Pihl Karlsson, G., Danielsson, H., Karlsson, P.E., and Hansen, K. Submitted. Wet deposition of inorganic nitrogen and sulphur compounds in Sweden during six decades, 1955-2014. Submitted to Atmospheric Environment.

Folmer, H. and van Ierland, E. 1989. Valuation methods and policy making in environmental economics. Studies in Environmental Science 36.

Fölster, J., Kyllmar, K., Wallin, M. & Hellgren, S. 2012. Kväve- och fosfortrender i jordbruksvattendrag - Har åtgärderna gett effekt? SLU Rapport 2012:1.

Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B., Cosby, B.J. 2003. The nitrogen cascade. Bioscience 53:341–356.

Germundsson C. 2006. Strötorvsanvändning i djurstallar – en litteraturgenomgång. Examensarbete inom lantmästarprogrammet. Projektrapport nr 6, Institutionen för jordbrukets biosystem och teknologi, Sveriges lantbruksuniversitet, Alnarp. [in Swedish].

GME 2017. Nitrogen Input in the Biosphere – First nitrogen report from the Federal Government, German Ministry of Environment, 2017.

Gravergaard, M., Thorsøe, M.H., Kjeldsen, C. and Dalgaard, T. 2016. Evaluating public participation by the use of Danish water councils – prospects for future public participation processes. Outlook on Agriculture 2016, Vol. 45(4) 225–230. DOI: 10.1177/0030727016675691.

Grönroos, J. 2014. Maatalouden ammoniakkipäästöjen vähentämismahdollisuudet ja –kustannukset, Ympäristöministeriön raportteja 26 | 2014

Grönroos, J., Munther, J., and Luostarinen, S. (2017) Calculations of atmospheric nitrogen and NMVOC emissions from Finnish agriculture, In Reports of The Finnish Environment Institute 37, p 60, Finnish Environment Institute

Hansen, N.M., Henriksen K., Sommer S.G. 2006. Observations of production and emission of GHG and ammonia during storage of solids separated from pig slurry: effects of covering. Atmospheric Environment 40, 4172-4181.Hansen, B., Thorling, L., Dalgaard, T. and Erlandsen, M. 2011. Trend reversal of nitrate in Danish groundwater – a reflection of agricultural practices and nitrogen surpluses since 1950. Env. Sci. Technol. 45 228–234.

Hellstedt, C., Cerruto, J., Nilsson, M. and McCann, M. 2014. Nordic initiatives to abate methane emissions – A cathalogue of best practices, ANP 2014:741, Nordic Council of Ministers, http://dx.doi.org/10.6027/ANP2014-741

Hellsten, S., Dalgaard, T., Rankinen, K., Tørseth, K., Kulmala, A., Turtola, E., Moldan, F., Pira, K., Piil, K., Bakken, L., Bechmann M. and Olofsson, S. 2017. Nordic nitrogen and agriculture - Policy, measures and recommendations to reduce environmental impact, Nordic Council of Ministers, TemaNord 2017:547. ISSN 0908-6692.

Hellsten, S. 2017. Ammonia emissions in Sweden – Inventories, projections and potential for reduction, IVL-Report C237.

Howard, C., Sutton, M.A., Oenema, O. and Bittman, S. 2015. Chapter 10: Costs of ammonia abatement: Summary, conclusions and policy context. In: Reis S, Howard CM, Sutton MA (eds) Costs of ammonia abatement and the climate co-benefits. Springer, Dordrecht, pp 263–281.

Iivonen, S. 2008. Ympäristöturpeet ja niiden käyttö, Raportteja 32, ISBN: 978-952-10-4156-3 [in Finnish]

Jensen, P.N., Blicher-Mathiesen, G., Rolighed, J., Børgesen, C.B., Olesen, J.E., Thomsen, I.K., Kristensen, T., Sørensen, P. & Vinther, F.P. 2015. Revurdering af baseline. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, 60 s. - Teknisk rapport fra DCE - Nationalt Center for Miljø og Energi nr. 67. [In Danish] dce2.au.dk/pub/TR67.pdf

JTI, Swedish Institute of Agricultural and Environmental Engineering. 2014. Minska utsläppen av växthusgaser från stallgödsel – Praktiska Råd – greppa näringen, N2 22, oktober 2014.

Karlsson, J., Röös, E., Sjunnestrand, T., Pira, K, Larsson, M., Hassellund Andersen, B., Sørensen, J., Veistola, T., Rantakokko, J., Manninen, S. and Brubæk, S. 2017. Future Nordic Diets – Exploring ways for sustainably feeding the Nordics, Nordic Council of Ministers, TemaNord 2017:566.

Karlsson, P.E., Pihl Karlsson, G., Hellsten, S. och Akselsson, C. 2018. Utvecklingen av en indikator för totalt nedfall av kväve till barrskog inom miljökvalitetsmålet Ingen övergödning. IVL Rapport C286. [in Swedish].

KI, Konjunkturinstitutet, 2014. Miljö, ekonomi och politik, Konjunkturinstitutet 2014. ISSN 2001-3108, ISBN 978-91-86315-56-6.

Kijek, T., Nowak, A., Kasztelan, A. and Krukowski, A. 2015. Agricultural total factor productivity changes in the new and the old European Union members. In (Ed: Raupelienè. A.) Proceedings of the /th International Scientific Conference Rural Development 2015. Article DOI: http://doi.org/10.15544/RD.2015.084 Krupa, S.V. 2003. Effects of atmospheric ammonia (NH_3) on terrestrial vegetation: a review. Environmental Pollution 124, 179e221.

Launto-Tiuttu, A., Heikkinen, J., Koskinen, J., Lankinen, E., Lundström, E., Puustinen, S., Röytiö, J., Vartiainen, E., Wilander, S; Yli-Heikkilä, K. 2014. Targeted measures bring the greatest benefits for environmental protection in agriculture - final report of the TEHO Plus project (2011–2014), TEHO Plus project publication 9/2014.

Leip, A., Billen, G., Garnier, J., Grizzetti, B., Lassaletta, L. et al. 2015. Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. Environmental Research Letters, IOP Publishing, 2015, 10 (11), pp.115004. <10.1088/1748-9326/10/11/115004>. <hal-01261336>

Luostarinen, S., Grönroos, J., Tampio, E., Uusitalo, R., Lemola, R., Lehtonen, E., Lehtoranta, S., Pitkänen, H., Alhainen, V., Turtola, E. 2018. Luonnonvara- ja biotalouden tutkimus. Manuscript.

Luke 2018, Luke – Statistics database, Natural Resources Institute Finland, http://statdb.luke.fi/PXWeb/pxweb/en/LUKE/LUKE__04%20Metsa__08%20Muut__Energia/11.00_Turpeen_tuotanto_kulutus_ja_ulkomaank.px/?rxid=001bc7da-70f4-47c4-a6c2-c9100d8b50db

MAF, 2018. Action plan to reduce ammonia emissions from agriculture in Finland, Publications of the Ministry of Agriculture and Forestry, 1b/2018, ISBN 978-952-453-973-9, ISBN PDF: 978-952-453-974-6.

McCrackin, M.L., Gustafsson, B.G., Hong, B., Howarth, R.W., Humborg, C., Savchuk, O.P., Svanbäck, A. and Swaney, D.P. 2018. Opportunities to reduce nutrient inputs to the Baltic Sea by improving manure use efficiency in agriculture. Regional Environmental Change (2018). https://doi.org/10.1007/s10113-018-1308-8.

Montalvo, G., Pineiro, C., Herrero, M. and Bigeriego, M. 2015. Ammonia abatement by animal housing techniques. In: Reis S, Howard CM, Sutton MA (eds) Costs of ammonia abatement and the climate co-benefits. Springer, Amsterdam.

Nielsen, O.K., Plejdrup, M.S., Winther, M., Mikkelsen, M.H., Nielsen, M., Gyldenkærne, S., Fauser, P., Albrektsen, R., Hjelgaard, K.H., Bruun, H.G. and Thomsen, M. 2018. Annual Danish Informative Inventory Report to UNECE, Emission inventories from the base year of the protocols to year 2016, Scientific Report from DCE – Danish Centre for Environment and Energy No. 267 2018, Aarhus University, Department of Environmental Science. NIRAS Konsulenterne. 2009.

NIRAS Konsulenterne. 2009. Forudsætninger for de økonomiske beregninger af BAT teknologier. Revidering av økonomiske oplysninger i BAT blade, NIRAS Konsulenterne, Maj 2009.

NOU, 2015. NOU 2015:15, Sett pris på miljøet. Rapport fra grønn skattekommisjon. www.Regjeringen.no.

Ocké, M.C., Toxopeus, I.B., Geurts, M., Mengelers,M.J.B., Temme ,E.H.M. and Hoeymans, N. 2017. What is on our plate? Safe healthy and sustainable diets in the Netherlands, RIVM Report 2017-0024. DOI 10.21945/RIVM-2017-0024

OECD, 2018. Innovation, Agricultural Productivity and Sustainability in Sweden, OECD Food and Agricultural Reviews, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264085268-en

Rankinen, K., Keinänen, H., Cano Bernal, J.E. 2016. Influence of climate and land use changes on nutrient fluxes from Finnish rivers to the Baltic Sea. Agriculture, Ecosystems and Environment, 216: 100-115.

Reis, S., Howard, C. and Sutton, M. (eds) 2015. Costs of Ammonia Abatement and the Climate Co-Benefits, ISBN 978-94-017-9721-4, ISBN 978-94-017-9722-1 (eBook), DOI 10.1007/978-94-017-9722-1, Springer Dordrecht Heidelberg New York London.

Rodhe, L., Casimir, J. and Sindhöj, E. 2018. Possibilities and bottlenecks for implementing slurry acidification techniques in the Baltic Sea Region, RISE Rapport 2017:47.

Ruser, R. and Schulz, R. 2015. Inhibition of nitrification to mitigate nitrate leaching and nitrous oxide emissions in grazed grassland: a review. J Soils andSediments 16:1401-1420.

Santonja, G.G., Georgitzikis, K., Scalet, B.M., Montobbio, P., Roudier, S and Sancho, L.D. 2017. Best Available Techniques (BAT) Reference Document for the Intensive Rearing of Poultry or Pigs; EUR 28674 EN; doi:10.2760/020485

SBA, Swedish Board of Agriculture. 2010. Styrmedel för minskade utsläpp – Bilaga 1 till Rapport 2010:10 Minskade växtnäringsförluster och växthusgasutsläpp till 2016 – förslag till handlingsprogram för jordbruket, the Swedish Board of Agriculture, Jordbruksverket, [in Swedish].

SBA, Swedish Board of Agriculture. 2013a. Actions against Plant Nutrient losses from Agriculture, the Swedish Board of Agriculture, Jordbruksverket, OVR125GB Oct 2013.

SBA, Swedish Board of Agriculture. 2013b. Köttkonsumptionen i siffror – Utveckling och orsaker, Jordbruksverket, Rapport 2013:2. [in Swedish].

SEA, 2017. Produktion och användning av biogas och rötrester 2016. Swedish Energy Agency, Energimyndigheten. ES 2017:07, ISSN 1654-7543. [in Swedish].

SEGES, 2015. Status, økonomi og overvejelser ved forsuring af gylle, Planteavlsorientering – 279, SEGES, 2014 [in Danish].

Selvik, J.R., Tjomsland. T., Høgåsen, T. 2012. TEOTIL: Kildefordelte tilførsler av nitrogen og fosfor til norske kystområder i 2011 - tabeller og figurer. NIVA-rapport 2998/2012. 22p.

SEPA, Swedish Environmental Protection Agency, Naturvårdsverket. 2018. Informative Inventory Report Sweden 2018, Submitted under the Convention on Long-Range Transboundary Air Pollution, Swedish Environmental Protection Agency Report 2018.

SLU, Swedish University of Agricultural Sciences. 2010. Axel 2 – utvärdering av åtgärder för att förbättra miljön och landskapet. Bilaga till Halvtidsutvärderingen av landsbygdsprogrammet, Institutionen för ekonomi, SLU, Uppsala.

Statistics Norway 2018. Emissions of acidifying gases and ozone precursors, Table 08941: Acidification precursors, ozone precursors etc., by source, energy product and pollutant 1990-2016, Statistisk Sentralbyrå, (Statistics Norway), accessed 5th of March, 2018, https://www.ssb.no/en/statbank/list/agassn?rxid=0bf481b4-e645-4900-bc9e-cce667fbaa4e

Statistics Sweden, 2014. Use of fertilisers and animal manure in agriculture 2012/13, MI 30 Sm 1402, Statistics Sweden. In Swedish, English summary.

Statistics Sweden, 2017. Use of fertilisers and animal manure in agriculture 2015/16, MI 30 Sm 1702, Statistics Sweden. In Swedish, English summary.

Sutton, M., Hoffman, M., Baker, E., Launois, L., Einarsson, R., Isepp, K., Tolotto, M., Holmberg, L., Ravnborg, H., Pira, K., Hellsten, S. and Wichink-Kruit, R. 2018. Sectors and solutions: Opportunities and challenges to reduce air pollution from agriculture, In (ed) Engleryd, A. & Grennfeldt, P. Saltsjöbaden VI Workshop 2018 – Clean Air for a Sustainable Future – Goals and challenges, Gothenburg 19-21 March 2018, TemaNord 2018:540.

Sutton, M.A., Reis, S., Baker, S.M.H. (eds). 2009. Atmospheric ammonia – detecting emission changes and environmental impacts – results of an expert workshop under the convention on long-range transboundary air pollution. Springer, Heidelberg

Sutton, M.A., Howard, C., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (eds). 2011. The European nitrogen assessment. Cambridge University Press, Cambridge.

Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizzetti, B., de Vries, W., van Grinsven, H.J.M., Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E.A., Datta, A., Diaz, R., Erisman, J.W., Liu, X.J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R.W., Sims, T., Westhoek, H., Zhang, F.S. 2013. Our nutrient world: the challenge to produce more food and energy with less pollution. Global overview of nutrient management. Centre for Ecology & Hydrology, Edinburgh.

Sørensen, P. and Duus Børgesen, C. 2015. Kvælstofudvaskning og gødningsvirkning ved anvendelse af afgasset biomasse, DCA rapport, nr. 65, 2015. [In Danish with English summary]

Tybirk, P. 2015. Nutrient recommendations for pigs in Denmark, SEGES, Danish pig research centre, 2015.

The Danish Government 2013. The Danish Climate Policy Plan – Towards a low carbon society, 2012/2013:8, The Ministry of Climate, Energy and Building, Danish Government, August 2013. Electronic publication ISBN 978-87-93071-29-2.

UNECE, 2011, Reactive Nitrogen - Report by the co-Chairs of the Task Force on Reactive Nitrogen, ECE/EB.AIR/WG.5/2011/16.

UNECE, 2015. Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions, Published by the European Commission, Directorate-General Environment on behalf of the Task Force on Reactive Nitrogen of the UNECE Convention on Long-range Transboundary Air Pollution. http://www.unece.org/fileadmin/DAM/env/lrtap/Publications/Ammonia_SR136_28-4_HR.pdf

UNECE 2014. Guidance document on preventing and abating ammonia emissions from agricultural sources, ECE/EB.AIR/120. http://www.unece.org/fileadmin/DAM/env/documents/2012/EB/ECE_EB.AIR_120_ENG.pdf.

Valkama, E., Lemola, R., Känkänen, H. & Turtola, E. 2015. Meta-analysis of the effects of undersown catch crops on nitrogen leaching loss and grain yields in the Nordic countries. Agriculture, Ecosystems and Environment 203: 93-101.

van Vuuren, A., Pineiro, C., van der Hoek, KW., Oenema, O. 2015. Chapter 3: Economics of low nitrogen feeding strategies. In: Reis S, Howard CM, Sutton MA (eds) Costs of ammonia abatement and the climate co-benefits. Springer, Dordrecht, pp 35–51.

Vuorenmaa, J., Augustaitis, A., Beudert, B., Bochenek, W., Clarke, N., de Wit, H. A., Dirnböck, T., Frey, J., Hakola, H., Kleemola, S., Kobler, J., Krám, P., Lindroos, A.-J., Lundin, L., Löfgren, S., Marchetto, A., Pecka, T., Schulte-Bisping, H., Skotak, K., Srybny, A., Szpikowski, J.Ukonmaanaho, L., Váňa, M., Åkerblom, S., Forsius, M. 2018. Long-term changes (1990–2015) in the atmospheric deposition and runoff water chemistry of sulphate, inorganic nitrogen and acidity for forested catchments in Europe in relation to changes in emissions and hydrometeorological conditions. Science of the Total Environment 625: 1129-1145.

Westhoek H., Lesschen J.P., Leip A., Rood T., Wagner S., De Marco A., Murphy-Bokern D., Pallière C., Howard C.M., Oenema O. & Sutton M.A. 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.) Centre for Ecology & Hydrology, Edinburgh, UK.

Willems, J., van Grinsven, H.J.M., Jacobsen, B.H., Jensen, T., Dalgaard, T., Westhoek, H., Kristensen, I.S. 2016. Why Danish pig farms have far more land and pigs than Dutch farms? Implications for feed supply, manure recycling and production costs. Agricultural Systems 144, 122–132. https://doi.org/10.1016/j.agsy.2016.02.002

Windolf, J., Blicher-Mathiesen, G., Carstensen, J., Kronvang, B., 2012. Changes in nitrogen loads to estuaries following implementation of governmental action plans in Denmark: A paired catchment and estuary approach for analysing regional responses. *Environmental Science and Policy 24, 24-33*.

Wreford, A., Ignaciuk, A. and Gruère, G. 2017. Overcoming barriers to the adoption of climate-friendly practices in agriculture, *OECD Food, Agriculture and Fisheries Papers*, No. 101, OECD Publishing, Paris. http://dx.doi.org/10.1787/97767de8-en