Nitrogen and agriculture in the Nordic countries - policy, measures and the way forward

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Abstract

During the past twenty years, the Nordic countries (Denmark, Sweden, Finland and Norway) have introduced a range of measures to reduce Nitrogen (N) emissions to air and the losses of N through leaching and run-off to the aquatic environment. 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 are at different levels regarding agricultural N flows and mitigation measures, and therefore they are facing different challenges and barriers. In Norway subsidies are widely used, but mainly focusing on phosphorus (P), whereas in Denmark N is the primary target, and command and control regulations are the main strategy to reduce losses. In Sweden and Finland, voluntary actions combined with subsidies are important targeting both N and P.

The aim of this study was to compare and discuss the present situation 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 for inspiration abroad.

To further reduce N losses from agriculture, the four countries will have 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 approaches, regulation approaches, tax approaches and subsidies approaches, but the difficulty is finding the right balance between these policy options.

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 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.

1. Introduction

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

To this, the Haber-Bosch process, which captures atmospheric N_2 to form reactive N (ammonium and nitrate), made it possible to intensify agriculture and increase food production. As a result, the production of mineral fertilizers is 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 cycle along with the easily soluble nitrates 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^-), 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 area compared with the other Nordic countries, due to the high percentage of agricultural area (62%), see Table 1. Denmark also 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. 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)	Agricultural land (%)	Meat production (thousand tonnes)				
				pig	cattle	poultry	sheep	Total
Denmark	41990	26110	62	1,530	124	164	2	1,820
Sweden	407310	30398	7.5	240	132	159	5	536
Finland	303910	22734	7.5	179	85	129	1	395
Norway	365245	9061	2.5	137	85	101	27	351

A higher share of farm land, an intensive livestock production (primarily pigs), higher farming intensity and the sandy soils have in general brought about more severe N problems in Denmark compared with the other Nordic countries. Consequently, from 1985 and onwards a series of political action plans to mitigate losses of N and other nutrients were implemented in Denmark (Dalgaard et al., 2014). according to the EU Nitrates Directive, Denmark has designated the whole territory as nitrate vulnerable.

In Finland, the first concerns of eutrophication arose already in the 1960's, and increasingly since 1995 a set of legal and voluntary instruments, targeting agricultural nutrient losses to waters, have been implemented. Previously, increased N inputs and clearing of new fields gradually increased agricultural N losses in Finland, but since 2007, N loads from agriculture (2007-2012) have been estimated to have decreased by about 10% (Rankinen et al., 2016). All agricultural land in Finland is regulated through the Nitrates Directive, which sets maximum N fertilization levels to all agricultural crops. Moreover, the voluntary Agri-Environmental Program, adopted by about 90% of farmers since 1995, sets lower maximum levels of fertilization and other measures (e.g. manure management and crop cover) to reduce N losses.

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 from 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 high risk areas of erosion and P losses. However, due to low focus on N in Norway, the N surpluses are higher per area agricultural land in some Norwegian areas compared with the other Nordic countries (Bechmann et al., 2014).

In Sweden legislation on storage and spreading of manure were introduced already in the 1980's. Since then further and expanded rules have been introduced. The measures have targeted both reduced losses of P and N. In 2001, the voluntary advisory Program "Focus on nutrients" ("Greppa näringen") was initiated, in order to meet national environmental objectives regarding e.g. eutrophication and reduced climate impact. Also support schemes within the Rural Development Program (RDP), e.g. for catch crops, have been important for the decrease in nutrient loads that has been obtained. In Sweden, 75% of the agricultural land has been classified as nitrate vulnerable according to the EU Nitrates Directive.

The aim of this study was to compare and discuss the present situation 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 for inspiration abroad.

2. N management in the Nordic countries

2.1 Measures to reduce ammonia emissions

Agriculture is the main responsible sector for ammonia emissions in the Nordic countries. The agricultural sector therefore has the largest potential to reduce emissions of ammonia. 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	**Comment**	**Implementation**
Low N feed	**Reduction potential:** about 20% (van Vuuren et al., 2015) **Cost:** -0.5 - 0.5 € (van Vuuren et al., 2015). Reduce ammonia emissions at many stages of manure management, from excretion in livestock houses, through storage of manure to application on land. Also positive effects on animal health and indoor climate. This measure could be increased by providing information and counselling about low N feed.	In Denmark, phase feeding of livestock (i.e. the protein content of the feed is adjusted over the lifetime of the livestock) has been successful in reducing ammonia emissions from the pig industry. In Sweden, ”Focus on nutrients” inform farmers about the advantages of low N feed. In Finland, phase feeding is utilized and the advisory systems deliver information on N requirement during different feeding phases.
Low emission housing	**Reduction potential:** 20-90% (Bittman et al., 2014) **Cost:** 0-20 €1) (Bittman et al., 2014; Montalvo et al., 2015). Measures to reduce the surface 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.	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. In Sweden, ”Focus on nutrients” inform farmers about measures for low emission housing.
Air purification	**Reduction potential:** About 60% (assuming about 20% of the ventilation capacity). (NIRAS, 2009). **Cost:** 2.5-17 € (NIRAS, 2009). Options to treat the air ventilated from animal housing, e.g. acid scrubbers to treat the exhaust air. This measure could be increased by setting rules and demanding air purification in conjunction with permissions for new or expanded operations.	This is an expensive measure which is not broadly used in the Nordic countries. Swedish animal buildings often have natural ventilation, which is not suitable for air purification filters. In Denmark, new or expanding housing facilities may be required to have purification of ventilated air (due to ammonia or odor problems). In Norway, the technique has been implemented on a voluntary basis by a few agricultural producers.
Covered storage	**Reduction potential:** 50-95% depending on type of cover (SBA, 2010). **Cost:** 0.5-5 € (SBA, 2010). 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.	All countries have regulations regarding the storage of manure. Danish regulations comprise e.g. minimum storage capacity, no runoff from manure heaps and mandatory slurry tank floating barriers. Crusts (typically straw) or lids (typically of the “tent” type) are mandatory in Denmark. In Sweden, all livestock farms must have sufficient manure storage. For farms with more than 100 animal units the minimum storage capacity is 8 to 10 month 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. In Finland, all new slurry and dry manure storages must be covered and minimum storage capacity is 12 months. In Norway, minimum storage capacity for 8 month is required, but no cover is required. 20% of storages in Norway are not covered (Bechmann et al., 2016b).
Low ammonia application of manure	**Reduction potential:** 45-90% depending on type of manure and time after spreading (SBA, 2010). **Cost:** About 0.5-1 € (SBA, 2010). Means to distribute manure to minimize surface exposure, i.e. by placing it underneath the soil, e.g. band application, shallow injection or direct incorporation. Stricter regulations for both slurry, urine and digested manure could be an effective measure.	All Nordic countries have regulations for when, how and where to spread manure. For instance, in Denmark broadcasting has been banned since 2002 and there is also a ban on winter spreading of slurry for spring crops. In Denmark the use of application techniques are enforced by command and control. There are set standards for which application techniques that are allowed on which type of fields. In Sweden, sensitive areas have stricter regulations regarding when manure spreading should occur, and how quickly the manure should be incorporated into the soil, and also restrictions on type of spreading technique. In Norway, subsidies are provided for band application and direct injection. The spreading period is limited to 15th Feb to 1st Sept for surface application or 1st Nov for incorporation. In Finland, manure must be incorporated within 24 hours after spreading, with a few exceptions (e.g. application of fertilizer on plants with a hose sprayer or over an entire area). Stricter regulations apply on sections of arable land parcels with a slope of at least 15%. The application of manure and organic fertilizers in fields is prohibited from 1st Nov to 31st Mar (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	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 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. In Denmark, 10-20% of the use of mineral fertilizers is urea. Southern Sweden has regulations that urea should be incorporated into the soil within 4 hours.
Using peat during storage of solid manure	**Reduction potential:** About 50% (SBA, 2010) **Cost:** About 0.5 € (SBA, 2010). 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.	The use of peat as litter is very limited in many Nordic countries today. In Finland 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. Germundsson (2006) has estimated the use in Sweden to be about 200 000 and 300 000 m^3 per year.
Acidification of slurry	**Reduction potential:** About 80% during storage and 70% during spreading (NIRAS, 2009) **Cost:** 3-14 € (NIRAS, 2009). 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.	Acidification of slurry is not broadly used in the Nordic countries, except for Denmark, where 18% of the slurry was acidified in 2014 (SEGES, 2015). In Denmark, acidification is particularly carried out in connection with application. 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 UNECE CLRTAP Task Force on Reactive Nitrogen (TFRN) 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. For instance, TFRN concluded that low emission spreading of liquid manure is the most efficient mitigation approach to reduce ammonia emissions, and also offers cost-savings for agricultural producers due to reduced inputs of mineral fertilizers. 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. In Finland all new slurry storages need to be covered, hence the share of covered storages increases continuously, resulting in decreasing ammonia emissions from manure storage (MAF, 2018).

Also in Norway, changing into low emission application techniques has been identified to be the most efficient measure to reduce ammonia-emissions (Bechmann et al., 2016b). Emission reductions have been estimated to be 1500-2000 t N/yr by changing the manure application method.

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, see Table 3. In Norway, the situation is even worse, with 88% of the slurry being applied using broadcast spreading. 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) estimates that it will continue to increase steadily in the future, even without regulations.

Table 3. Application techniques for slurry in the Nordic countries (%). Source: Rodhe et al., 2018 and Bechmann et al., 2016b.

Country	Broadcast spreading (%)	Band spreading (%)	Injection (%)
Denmark1)	0	853)	15
Finland1)	35	34	31
Sweden2)	282)	682)	4
Norway4)	88	12	0

1) Estimated by national experts
2) 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).
3) Including 20% acidified slurry.
4) Bechmann et al., 2016b.

2.2 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), or for instance as the case in Denmark, the implementation of measures are required by national legislation and demands for cross compliance to receive EU subsidies. 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 4 provides an overview of measures to reduce nitrate leaching and level om implementation in the Nordic countries.

Table 4. 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	Comment	Implementation
Manure management (see also Table 2)	**Cost:** 42-840 € (420-8370 SEK) (Agrifood, 2015).	Effective utilization of organic fertilizers and slurry as well as closed periods of spreading is important to reduce nitrate leaching. Maximum N fertilization limits are set within the Nitrates Directive. Advisory services and education exist in each country regarding improved utilization of manure and fertilizer. Denmark has strong restrictions in N application compared with Sweden, Norway and Finland. In Norway, subsidies are provided for band application and direct injection of manure. In Finland, financial support is available for injection of slurry. In Sweden, subsidies may be provided for direct injection of manure but this is decided by the County Administrator Boards, hence differs within the country.
Digestion of manure	Makes the nutrients more easily accessible for the plants.	In Sweden, the development of biogas is currently being implemented and an investment support for manure digestion plants exists. 41 manure digestion farm

		plants existed in Sweden in 2016 (SEA, 2017). In Norway, subsidies are given to manure used for biogas. In Denmark, about 7% of the manure production was digested in 2012. In 2020 the assumption is that this number will have increased to 19% (Jensen et al., 2015). In Finland 6% of pig slurry and about 1% of other manure is presently digested. Investment support can be applied for construction of a biogas plant.
Catch crops	**Cost:** 1-3 € (5-19 DKK), (Eriksen et al., 2014). If changes in the crop rotation are required the cost will be higher, 21-32 € (157 DKK). A catch crop is grown between two main crops and take up the plant nutrients left in the soil after harvest, hence reduces leaching.	Sweden and Norway provide investment support (subsidies) for catch crops. 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. In Finland, catch crops are supported and regulated within the Finnish Agri-Environmental Program.
Combined catch crops and spring tillage	**Cost:** 10 € (96 SEK), (SLU, 2010) Reduce nutrient leaching during October to March. Spring tillage is associated with a lower risk of nutrient leaching than during autumn, but may increase the use of pesticides during the growing season.	In Sweden, investment support is currently provided both to catch crops and spring tillage. In Norway, subsidies are given for catch crops in combination with spring tillage. In Denmark, 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 on sandy soil from Feb 1st and on sandy clay and organic soil from Oct 1st, and on clay soil from Nov 1st. In Finland both catch crops and reduced tillage are supported within the current Agri-Environment Program.
Wetlands (re-establishment and construction)	**Cost:** 4 € (31-33 DKK), (Eriksen et al., 2014), 5-8 € (49-80 SEK) (SLU, 2010) May act as N (and P) traps.	Investment support is provided for the construction of wetlands in Denmark, Finland, Norway and Sweden, and for the maintenance of wetlands in Norway and Sweden. Denmark plans to build many constructed wetlands to reduce leaching.
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.	In Denmark, investment support is provided to low N grasslands in environmentally sensitive areas. In Finland, environmental management grasslands are part of the Agri-Environmental Program. In Sweden 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.

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). Slurry close periods are also effective 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 (with lower N surplus) at a low costs resulting in a lower N surplus (Bechmann et al., 2014). Suggested measures include among others 1) improved nutrient management planning based on average yield instead of highest expected yield as a basis for N application, 2) split N application, 3) precision N application and 4) 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). Already in the end of the 1990's, legislation on when, and how fast, manure should be incorporated into the soil, was introduced. About 24% of surface spread manure (both solid and liquid) is directly incorporated into the soil (Statistics Sweden, 2014). Furthermore, reduced or postponed tillage have also been used as measures 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 have also been discussed.

In Finland, the Nitrates Directive is implemented in the whole country. It sets annual maximum amounts of soluble N (kg ha^{-1}) for various plants as well as limits the amount of total N that can be given in manure and organic fertilizer products containing manure. From 1st Sep 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, that has been adopted by the majority of farmers, sets slightly lower application maximums. 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 waters. Recently, cover crops were included with high potential to reduce N leaching in the Nordic countries (Valkama et al., 2015).

2.3 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 will yield lower N_2O-emissions. Table 5 provides an overview of measures to reduce emissions of N_2O from the agricultural sector in the Nordic countries.

Table 5. Overview of measures to reduce emissions of nitrous oxide (N_2O) from agriculture in the Nordic countries. Updated from Hellsten et al. (2017).

Measure	Comment	Implementation
Effective use of manure and fertilizers	Efficient N use will contribute to overall lower N application and hence lower emissions of N_2O. During manure application, time and amount of manure should be adjusted to the need of crops. In a Nordic climate, spring application is more efficient that autumn application.	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 nothing. Covering solid manure heaps with a plastic sheet may reduce emissions of N_2O.	See Table 2.
Rapid incorporation of manure after application	Likely reduces losses of N_2O. Some methods for low ammonia application of manure may increase emissions of N_2O, but from a holistic perspective it is still advantageous regarding greenhouse gases.	See Table 2.
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 4.
Catch crops	Reduce nutrient leaching, and likely also reduces losses of N_2O (but may	See Table 4.

	increase the use of pesticides)	
Spring tillage	Spring tillage likely reduces losses of N_2O (as long as the soil is not compacted).	See Table 4.
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.

N_2O emissions from agricultural soils depend on process rates (nitrification and denitrification), and their product stoichiometry (Bakken and Frostegård, 2017). Traditional approaches to mitigate emissions, IPCC recommendations for instance, have targeted the process rates, rather than the stoichiometry. Typical examples are:

- Reduced fertilizer levels (thus reducing the rates of nitrification and possibly denitrification).
- Optimizing fertilizer levels to match the assimilation by crops (thus reducing off-season nitrate leaching and denitrification in the soil and downstream).
- Digestion of manure prior to incorporation into the soil (reducing the amounts of available C, thus denitrification).
- Spring tillage (reducing off-season nitrification and denitrification).
- Adequate soil drainage and good soil structure, (to minimize denitrification). For instance, in peat soils, relatively high ground water levels reduce N_2O emissions.

Novel approaches to reduce N_2O emissions, target the ecology and regulatory biology of N transformations, e.g. by increasing soil pH or partial inhibition of nitrification (e.g. Qu et al., 2014; Russenes et al., 2016; Cayuela et al., 2014; Huang et al., 2014; Ruser and Schulz, 2015) . These novel approaches to reduce N_2O emissions require more research prior to implementation, both for elaborations and for validation of their effects on N_2O emissions in realistic agronomic field experiments.

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 either Command and Control measures, 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, general Command and Control measures (rules and regulations) are dominating. Most of the measures have been implemented as legislations, 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 joining 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.

In Sweden, measures to mitigate environmental impacts from agriculture are based on legislation, information campaigns and subsidies. A lot of focus has been on voluntary actions, primarily through the Swedish advisory program "Focus on nutrients", which has been running in Sweden since 2001 and has contributed to 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. 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).

There have also been agri-environmental projects with farm specific advisory efforts in the other Nordic countries but they have been short-lived and targeted smaller geographical areas than "Focus on nutrients". For instance, 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 and not so much on N. In Norway, the webpage "Tiltaksveilederen" (www.nibio.no/tiltak) present information on mitigation measures to reduce nutrient losses from agriculture.

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 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 N surplus and nitrogen use efficiency (NUE)

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. A surplus indicates potential environmental problems, while a deficit may indicate a decline in soil nutrient status. 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.

Denmark and Norway have a higher N surplus compared with Sweden and Finland, see Figure 1. Although Norway has the highest N surplus (which indicates potential environmental problems through N losses to water and air from agricultural soils), the agricultural area in Norway is small (2.5%). In Denmark on the other hand, more than 60% of the land area is being farmed.

Therefore the total N surplus (from the whole country) is about twice as big in Denmark compared with the other Nordic countries, see Table 6.

In Denmark, Finland and Sweden the N surplus has decreased since 1990, particularly in Denmark where it has decreased by more than 50%. This indicates that the N use efficiency (NUE) has increased in all Nordic countries, except Norway, during the past 25 years.

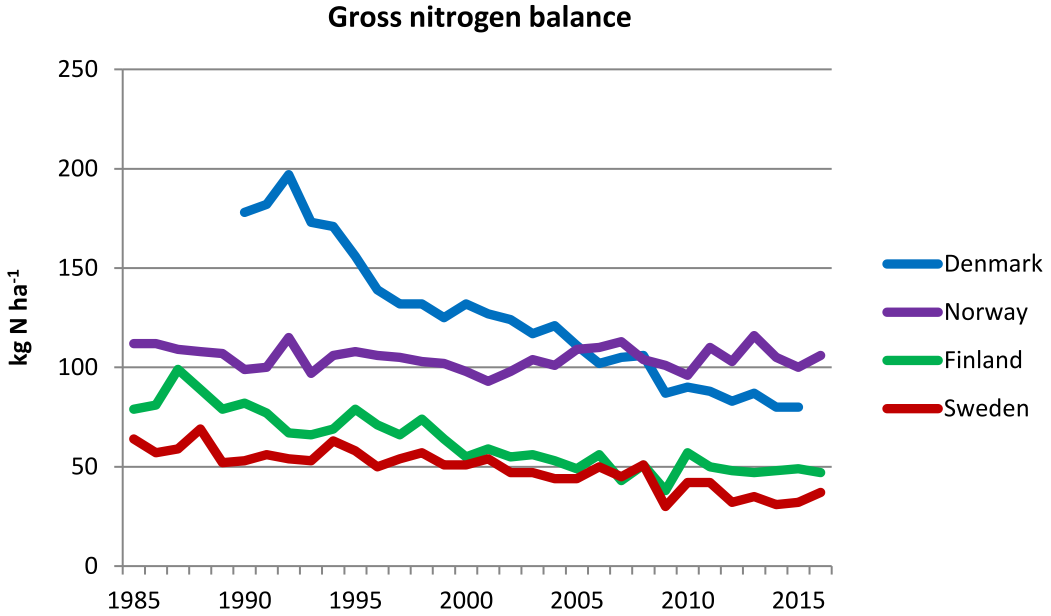

Figure 1. Gross nitrogen balance (kg N per ha of agricultural area), 1985-2016. Source: Eurostat (2018).

Table 6. Total N surplus from agricultural land in the Nordic countries (year 2015), based on data from FAO FAOSTAT and Eurostat (2018), see Table 1 and Figure 1.

Country	**Agricultural land (ha)**	**N surplus (kg ha^{-1})**	**Total N surplus (ktonnes)**
Denmark	2611000	80	209
Sweden	3039800	32	97
Finland	2273400	49	111
Norway	906100	100	91

3.2 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 1). The overall N use efficiency (NUE) for the agricultural sector has also increased during the same time period, from around 20-30% to 40-45% (Daalgard et al., 2014). As a result, the N load to marine waters has been reduced by 50% and the previously increasing trend of N content in groundwater has been turned into a decreasing trend (Hansen et al., 2011; Windolf et al., 2012).

This reduction has mainly been done by improving the nutrient utilization efficiency in agriculture as well as setting restrictions on the use of N fertilizer, which further gives the farmer an incentive to improve N use efficiency. Since the mid-1980s, a series of policy action plans to mitigate losses of N have been implemented in Denmark. However, despite large reductions in nitrate leaching and due to the high agricultural production in Denmark, with 62% of the land area being farmed, the targets set for the Water Framework Directive (WFD, 2000/60/EC) are sometimes exceeded, hence further reductions are still needed.

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 source runoff from agricultural land and point discharges from silos and manure storage systems. The system has been amended and adapted over the years. However, because the main focus was on reducing P losses the estimated losses of N from agricultural areas to marine waters increased by 11% from 1990 to 2011 (Selvik et al., 2012).

In Sweden, inorganic N leaching from agricultural land has decreased since the 1980's. Monitoring 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, improved N use efficiency, increased areas of grassland, improved handling of manure, more winter cereals and less spring cereals. In recent years, model calculations show that the decline seems to have slowed down, but it can be difficult to compare these model calculations with previous estimates.

In Finland, the N load from agriculture to waters has only decreased marginally in recent years, despite considerable reductions in fertilizer use and N field balances (Rankinen et al., 2016). The N balance has been reduced 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 the N load from agricultural land is even higher.

3.3 Ammonia emissions

Ammonia emissions in the Nordic countries (Figure 2, Table 7) mainly originate from agriculture. The agricultural sector contributes to about 96% of the ammonia emissions in Denmark, and approximately 90% on average in Finland, Norway and Sweden (Antman et al., 2015; Pira et al., 2016).

Denmark has had the largest reduction in emissions of ammonia by about 40% since 1990 (Nielsen et al., 2018). In Sweden and Finland the reduction was smaller, 12% in Sweden and 11% in Finland during the same time period (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 declined livestock numbers, reduced use of inorganic fertilizers and a more effective production (SEPA, 2018). At the same time, meat consumption and meat import has increased (SBA, 2013b), hence in principle the ammonia emissions have been transferred elsewhere. Despite the big reduction in ammonia emissions in Denmark during a long time period, ammonia emissions are no longer decreasing (since 2013, see Figure 2). Furthermore, projections indicate relatively small emission reductions in the coming years (Nielsen et al., 2018). It is therefore clear that action and incentives to reduce ammonia emissions are necessary to stimulate further reductions.

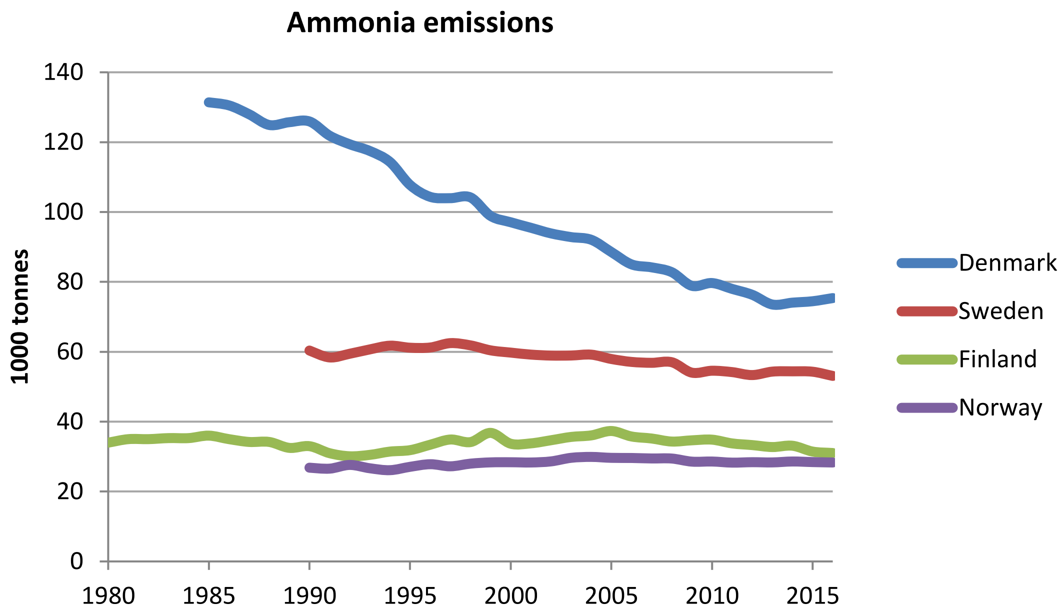

Figure 2. Ammonia emissions (thousand tonnes) in Denmark, Sweden, Finland and Norway during 1980-2016. Source: Nielsen et al, (2018); MAF (2018); SEPA (2018); Statistics Norway (2018).

Table 7. Ammonia emissions (thousand tonnes) in Denmark, Sweden, Finland and Norway. Source: Nielsen et al. (2018); MAF (2018); SEPA (2018); Statistics Norway (2018).

	1990	1995	2000	2005	2010	2015	2016
Denmark	126	108	97	89	80	74	75
Sweden	60	61	60	58	55	54	53
Finland	35	34	30	35	35	31	31
Norway	27	27	28	30	29	28	28

3.4 Nitrogen deposition

The nitrogen deposition in the Nordic countries has been reduced by about 25-30% since the 1980´s. 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 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., 2018). Since then, the wet deposition of both ammonium and nitrate have decreased by about 30%.

The total N deposition (nitrate and ammonium N) to coniferous forests in Sweden has decreased by 27% from 2001-2016 (Karlsson et al., 2018). During the same time period, Finland had 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).

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 8. 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 8.

Table 8. Ammonia emissions (ktonnes) 1990, 2005 and 2016 (based on data inTable 7) 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)	**NEC-target 2020** (change since 2005)	**NEC-target 2030** (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%)	-	-

In Denmark, concern has been raised that it will not be possible to reach the ambitious target of 24% until 2030. Current projections of ammonia emissions in Denmark show a continued decrease in emissions, but at a much slower pace than anticipated. Ammonia emissions are expected to decrease by 3% from 2015 to 2020, 5% from 2015 to 2030, with no further change until 2035 (Nielsen et al., 2018). Hence, by 2020, levels will have fallen by 18% (compared with 2005) and by 2030 and 2035 an additional 2%. This expected reduction (20% since 2005) does not add up to the 24% reduction target set out in the NEC-Directive. 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 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 for all livestock species, except cattle production, has resulted in reduced ammonia losses. This trend is expected to continue. Hellsten (2017) presented a scenario with four feasible measures which have the potential to reduce ammonia emissions in Sweden. The scenario included four mitigation measures, including low N feed for all pigs, coverage of all urine containers, doubling the use of peat during storage, applying low emission spreading techniques for urine and expanding the geographical area regulating manure incorporation within 4 hours. Implementing these four measures would result in an emission reduction of 3.5 ktonnes, which is not enough to reach the emission target of the NEC-directive for 2030. Additional reductions of 1.5 ktonnes are required. Hence, unless livestock numbers are reduced, even further measures are needed, e.g. lowering the crude protein further also for dairy cows and poultry, to its optimal level (without decreasing productivity), 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 livestock 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). Since 1990, ammonia-emissions from manure 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). The dominating method for manure spreading in Norway is broadcast spreading (see Table 3), which contributes to the high emissions of ammonia.

According to the Gothenburg Protocol, Annex IX, Sweden, Denmark and Finland have committed to having a national advisory code of good agricultural practice to control ammonia emissions (NAC). The Ammonia Framework Code (UNECE, 2015) is a good starting point for an NAC. Sweden and Denmark have NAC's (TFRN, 2017), and recently, the action plan to reduce ammonia emissions from agriculture in Finland has been prepared (MAF, 2018).

4.2 Co-benefits and trade-offs – between different pollutants and effects

Measures to reduce one pollutant can have both positive and negative effects on other pollutants, environmental problems, animal welfare etc. For instance, as ammonia losses decrease due to improved application methods of manure in the field, nitrate leaching can increase as more N is effectively applied in the soil. This can however be counteracted due to increased crop yields as more N is available for the crops, and a lower need to use mineral fertilizers. Understanding these complex interactions is important to be able to implement the most efficient mitigation measures to reduce N losses from agriculture.

The UNECE TFRN summarizes some of the co-benefits and trade-offs between N reduction measures and methane pollution (Dalgaard et al., 2015). For instance, covering slurry, manure and urine storages, not only reduces ammonia emissions, but also emissions of methane, which is an important greenhouse gas. On the other hand, some animal feeding strategies to reduce methane emissions may result in increased N excretion and emissions of ammonia. Furthermore, measures to reduce methane-emissions may enhance N_2O-emissions, e.g. establishment of a natural crust cover on the storage for swine slurry reduce emissions of methane and ammonia while increasing emissions of N_2O, but the size of these emissions are not quantified (Bechmann et al., 2016b).

4.3 Need for tools and knowledge to assess cost effectiveness, co-benefits and trade-offs

In a policy context, it is important to demonstrate that substantial economic and environmental benefits can be gained from reducing N losses from agriculture. As long as the most practical and feasible measures (which do not compromise productivity or other negative environmental effects) are not fully applied, a further focus on the more demanding approaches might not be needed, such as acidification of slurry or air purification in new and largely rebuilt pig and poultry houses.

Relevant cost data need to be provided together with effects of measures to make an integrated assessment of cost-effectiveness to support decision making. Hence there is a need for tools to assess combined effects of measures to reduce pollution to air and water. Using catchment scale economic-hydrological optimization models, Konrad et al. (2015) and Nainggolan et al. (2015) have demonstrated that synergies between two forms of pollutants such as N loading to the sea and greenhouse gases (GHG) emissions can be obtained when implementing measures with both effects at the optimal locations. Hereby abatement costs can be reduced, but for other pollutants the effects might also be neutral or even conflicting.

The GAINS model (Klimont and Winiwarter, 2015), and the FarmAC/Farm-N models are also examples of tools to evaluate combined effects (Dalgaard et al., 2014; 2017). The TargetEconN model developed for the Limfjords and Odense catchments in Denmark (Konrad et al., 2015) and the BALTCOST model for the Baltic sea (Hasler et al., 2014, applied for both N, P and GHG in Nainggolan et al., 2015) are other such examples.

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 Nitrates Directive (EC, 2018) have a high priority in all four countries, because the directive is binding even for Norway. Within the HELCOM countries, measures to prevent N leaching have very high priority, because most of the countries have reduction conditions set in the Baltic Sea Action Plan. Furthermore, the Water Framework Directive sets high priorities for N abatement for countries that border the sea. However, legal and regulatory issues have been highlighted regarding the implementation of the WFD (e.g. Jacobsen et al., 2017; Josefsson, 2012; Hovik and Hanssen, 2016; Voulvoulis et al., 2017).

Ammonia targets and reductions set in the Gothenburg Protocol and the NEC-Directive have significance for the ammonia mitigation strategies applied in the Nordic countries. Each EU member state should draw up, adopt and implement a national air pollution control program with a view to complying with its emission reduction commitments, and to contributing effectively to the achievement of the air quality objectives.

Failure to comply with the NEC-directive and occasional exceedances of targets set for the Water Framework Directive show that clearly, there is a need for further reductions. Furthermore, the projections into the future show that the current reduction plans are not sufficient.

Since the countries are at different levels 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 produce output (Dalgaard et al., 2014).

Pira et al. (2016) noted that within the Nordic countries, knowledge on mitigation practices applied in other Nordic countries is lacking. Mitigation measures and policies that work in one country may work in another country if the knowledge is there. However, an effective measure in one country may be difficult or very expensive to implement in another country, due to differences in the farming systems, soil conditions or regulatory frameworks. Policy and technological solutions used in Denmark might not be suitable to all areas and farm types in the other Nordic countries, but they could be relevant particularly in more intensive agricultural areas, e.g. in the south of Sweden.

In Denmark, initial agricultural measures were successful and effective because they were cost effective and in many cases beneficial for the farmer. On the other hand, the stringent regulations on fertilizer use in Denmark (EPA, 2017), are expensive and allow low flexibility to agricultural producers.

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.

5.1 Important to identify barriers before implementing new policy

Wreford et al. (2017) highlighted the importance of identifying and dealing with barriers before designing and implementing new agricultural policy strategies. These barriers relate to lack of information and awareness of effects and performance of mitigation measures, costs of adoption and dependency on practices and local conditions. Some of the barriers may even be created by existing policies that target other aims, e.g. subsidies to support production in marginal areas. Wreford et al. (2017) 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.

For instance, availability of funds could help to mobilize change and overcome economic barriers. Agricultural producers may be facing long term investment costs (maybe > 20 years) from implementing abatement measures. Furthermore, the high share of rented land with short-term contracts (particularly in Finland and Norway), may lead to lower investments as farmers cannot expect to get the benefit from their own investments.

Providing suitable subsidies may be one option to overcome problems with economic barriers. In Norway for instance, voluntary measures consist of investment support and subsidies, for instance to establish sedimentation ponds and wetlands. So one possible way forward to mobilize change may be to increase funds available to promote efficient mitigation measures, i.e. how the EU Rural Development Programs could be used to stimulate emission control further.

5.2 Information and voluntary actions are important for changed farming behaviour

The main purpose of advisory actions is to change both values and behaviors of the farmers. 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.

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 real value 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.

5.3 More stringent regulations, or not?

Given the competition between farms, it is important to lay down rules for environmental work that everyone should follow. 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.

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 in Norway, where focus has been more on P and not so much on N, 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. The ammonia emissions in Denmark were significantly higher in the early 1990's than the other Nordic countries due to the country's large animal production (Figure 2). However, it is unlikely that other countries with significantly lower animal density could reduce losses to the same extent solely by means of legislation. Furthermore, a heavy focus on regulatory approaches can have a negative impact on promoting the will of agricultural organizations and environmental authorities to move in the same direction. In Denmark, regulations have been an increased burden for farmers, and recently there has been a shift towards a more voluntary framework. Furthermore, 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 agricultural legislation in Sweden is already tough.

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. Applying slurry and urea more efficiently is not likely to work only on voluntary basis.

In all Nordic countries, there is a trend towards larger farms in order to maintain profitability in farming, 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.

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. This information campaign might therefore already have built a good basis for further development and acceptance of mandatory measures among Swedish farmers.

5.4 Shift towards more region based mitigation policies

Another trend regarding agricultural policies in the Nordic countries is that they are likely to move more towards geographically targeted policies. 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.

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 and Finland apply the Nitrates Directive on all agricultural land. In

Finland, the current voluntary Agri-Environmental Program is slightly tailored for the coastal areas.

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).

5.5 More efficient use of manure and mineral fertilizers

Norway has the highest average N-surplus among the Nordic countries (see Figure 1), which increases the risk of N losses to water and air from agricultural soils. This indicates that Norway needs to have more focus on the use of N fertilizer, i.e. a balanced application. In Norway, there has been no regulations at all regarding the amount of N fertilizer to be applied (except for 170 kg N ha^{-1} in the nitrate vulnerable zone). In Sweden, there is currently an exciting development in precision agriculture. Remote sensing, using satellite images together with vegetation maps are applied to improve the adaption of fertilizers to the N need of the crop.

McCrackin et al. (2018) concluded that manure is often not being used efficiently in the Baltic region, because the N use efficiency (NUE) generally tends to decrease with increasing livestock density. Denmark has managed to increase its NUE substantially, despite having a large number of livestock (particularly pigs). This reduction was mainly achieved through the Danish implementation of the Nitrates Directive which 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. 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. For instance, in some parts of Finland, manure are partly only dumped, i.e. not used in an efficient way in agriculture. If manure is used more effectively, it can (partly) substitute costly and energy-demanding mineral fertilizers.

5.6 Nitrogen tax

N-taxation may be a means to influence the supply of reactive N into the agricultural system. In Sweden, a tax on mineral fertilizers was introduced in 1984 to reduce N pollution, but it was abolished in 2009. A reintroduction of the tax has been discussed in recent years. The National Institute of Economic Research (NIER) in Sweden suggests that the tax should be re-implemented, as a means to reduce the use of mineral fertilizers (KI, 2014). NIER refers to the lack of effective policy instruments to reduce the supply of N through fertilization. However, in Sweden, the previous N tax reduced emissions of N_2O by only 2% because the Swedish N efficiency was already high. The effect of the previous N-taxation in Sweden, and the reasons for abolishing it, therefore need to be assessed further in order to better understand the effectiveness of a potential new N-taxation.

Also Norway had a tax on mineral fertilizers (1988-2000). In Norway, a reintroduction of the tax of 2.80 NOK (0.3 €) per kg of N has recently been suggested to reduce emissions of N_2O (NOU, 2015:15). However, also in Norway, the effectiveness of the tax compared with other measures has been questioned (Bechmann et al., 2016b). 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 1990's was able to efficiently reduce P fertilization.

5.7 New innovation

Denmark has been a pioneer among the Nordic countries when it comes to utilise and develop knowledge and techniques to increase the utilisation of N in manure, e.g. trailing hose slurry application techniques, acidification of slurry (either in housing or prior to application) and phase feeding of livestock (the protein content of the feed is adjusted over the lifetime of the 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 has later been revised. Today, initiatives to identify possibilities and obstacles to implement slurry acidification in the Baltic Sea Region are currently running (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. 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. Currently air scrubbers are not working sufficiently during winter time, because they are inefficient in a cold climate.

5.8 A new "30% club"

Sutton et al. (2018) proposed a new "30% club" for ammonia. This approach was adapted for sulphur (S) emissions in the 1980's and was represented by a group of European and North American countries that agreed to reduce their S emissions by at least 30% (Folmer and van Ierland, 1989). A new "30% club", would offer the opportunity for countries to share experiences and best practices in meeting the ammonia goals and potential benefits also for reducing nitrate leaching and emissions of N_2O.

If a "30% club" for ammonia emissions would have been introduced in 1990, Denmark would have been a suitable candidate to demonstrate leadership in improving N use efficiency on farms, as the ammonia emissions in Denmark have been reduced by 40% since then. If also the other Nordic countries would have joined the club then, this might have provided incentives and knowledge to achieve a higher emission reduction compared with today (11% reduction in Finland and 12% reduction in Sweden, and even an increase of 6% in Norway, see Table 8). Starting a "30% club", could be an important incentive and platform to promote more effective coordination and technology sharing of emission reductions. However, considering the large reductions in ammonia emissions already achieved in Denmark, the willingness to join such a club may not be there.

5.9 System change measures

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.

5.10 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. Policies to reduce nitrous oxides and nitrate are typically considered separately from those for ammonia. Ammonia emissions are part of the Gothenburg Protocol, but nitric oxide emissions are not.

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). Applying this perspective provides the opportunity to identify both ecologically and economically appropriate and balanced solutions. For instance, cost estimates of ammonia abatement and N oxides (NO_x) abatement indicate that most of the low cost measures for NOx emission have already been taken, while many of the low-cost measures for ammonia mitigation have yet to be taken (van Grinsven et al., 2013). 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).

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.

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.

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.
- 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.
- 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.

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