DNMARK: Danish Nitrogen Mitigation Assessment: Research and Know-how for a sustainable, low-Nitrogen food production

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Abstract The aim of this paper is to present the Danish Nitrogen Mitigation Assessment (www.DNMARK.org), a recently initiated 5-year multidisciplinary research alliance, focusing on the quantification of N flows and solutions scenarios for a more sustainable N use in Denmark. As one of the world's most agriculture intensive countries, with a long N regulation history, and state of the art monitoring of developments in key indicators for nitrogen losses, -use and –efficiency, Denmark is a case of special interest. Based on the results and recommendations from the European Nitrogen Assessment, DNMARK focus on all parts of the N cascade, and demonstrates results both at the landscape scale, and the national scale. The national N-flows and N-balance are accounted for 1990-2010, and methods for the downscaling of these results to regional pilot study areas are developed, together with approaches for the integrated assessment and modeling of the three main types of solution scenarios defined: i) New production chains with a more efficient use and recycling of N, ii) Geographically differentiated N-measures implemented by cost-effective instruments with localized planning and management of agricultural landscapes, and iii) Changed consumption patterns driving land use change and reducing N use.

Keywords Denmark, Nitrogen assessment, Nitrogen flows, Solution scenarios, Sustainable Nitrogen management

Aim and objective

Allying ten Danish research groups, more than twenty private and public stakeholder partners and key international partners, the overall objective of the DNMARK research alliance is to identify new pathways to significantly reduce N pollution and increase N efficiency, thus making Denmark leader in both resource efficient agriculture and mitigation of N-derived impacts from agricultural production on the environment, climate, public health and the economy.
Specifically the aims of the six research components (RC1-RC6) are to:

- Develop new methods to analyse time series of national N flows, and the effect of innovative mitigation scenarios on future agricultural production and food/biomass consumption (RC1).
- Assess the potential for locally targeted N mitigation measures at landscape-scale by analysing and modelling a number of pilot study areas with extensive spatial data coverage (RC2). Provide policy-relevant knowledge about catchment scale policy implementation, and hereby extend the research on cost-effectiveness and implementation of N measures (RC3).
- Enhance the collaboration between the individual Danish N research environments via PhD and post-doc research education on high-impact topics affecting N mitigation (RC4).
- Synthesize results, and communicate with farmers, consumers and the wider public how the detrimental effects of N can be reduced via changes in the management of N in the whole chain from production to consumption of food and bioenergy (RC5, RC6).

Background and hypothesis

The availability of industrial N fertilisers led to a large expansion of agricultural production (including livestock) and a reliable reactive N supply remains essential for the yield and stability of the agricultural production (Jensen et al. 2011). However, large losses of reactive N species, primarily from agricultural systems, have considerable adverse effects on the environment and human health. The European Nitrogen Assessment (Sutton 2011a, b) estimated the cost of reactive N emissions in Europe to be €70-320 billion per year, which outweighs the direct economic benefits of reactive N in agriculture. The highest costs were associated with reductions in air and water quality, and related health and nature effects, though these estimates are still associated with large uncertainties. The benefits of reducing N loading to improve water quality to comply with the Water Framework Directive have been estimated in Danish case studies (Hasler et al. 2010), indicating a positive benefit-cost ratio for many but not all catchments. Achieving cost-efficient mitigation of N losses is therefore highly sensitive to spatial targeting, the choice of policy instruments and farmers' responses to these (Beharry-Borg et al. 2012).
There are many different forms of reactive nitrogen (e.g. NH_3, NO_3, NO, N_2O and NO_X) that move through biogeochemical processes. This implies that one atom of N may take part in many environmental processes before it is immobilised or finally converted back to N_2. Referred to as the nitrogen cascade (Galloway et al. 2003), it explains why policy measures targeting one N species (e.g. nitrate or ammonia) may have large positive or negative effects on other species (e.g. nitrous oxide). These strong inter-linkages require a holistic approach to solve problems related to excess reactive N (Rygnestad et al. 2002).
Denmark has already implemented a number of measures to reduce losses of reactive N to the environment (Dalgaard et al. 2014; Kronvang et al. 2008) but there is still a need to make substantial further reductions. If major further reductions are to be achieved cost-effectively, it is essential to include measures that control the flows of N between agriculture and society (including urban waste) and between agriculture and other ecosystems (including the harvesting of biomass for bioenergy use). Since the flows of reactive N display large spatial variations, such measures will also need a stakeholder engagement process and landscape or catchment approach in order to maximise their efficiency.
Our central hypothesis is that the cycling of reactive N can be significantly improved through targeted measures at national, landscape and farm management scales, and that the design of policies to promote such measures requires a comprehensive understanding of the cycling of reactive N and its holistic impact on ecosystems and socio-economy at national and landscape scales. A clear understanding of the effectiveness of the incentive structures used to implement

measures as well as the influence of the social and institutional context of regulation is crucial. The development and use of this knowledge will help prioritise new, innovative measures and technologies for dealing with the N problem, thereby minimizing the costs and maximizing the benefits. We thereby hypothesise significantly higher cost-effectiveness of targeted regulation taking into account the local areas' vulnerability to the specific N pollution. In the DNMARK alliance, we believe that interdisciplinary research and the integration of the whole range of public and private stakeholders into the research chain, and two-way communication of research results, to be tested in the real world, are key to the identification of solution pathways for a more sustainable N management and utilisation. It is in particular in this area that we think DNMARK can move the frontier of interdisciplinary research, and facilitate the improvements needed in N management for a sustainable bioeconomy development.

Policy targets and solution scenarios will be used in the DNMARK project to structure discussion with stakeholders and promote collaboration between the constituent Research Components. The three policy targets will be to reduce losses of: 1) NO_3^- to comply with the EU Water Framework Directive, 2) NH_3 to comply with the Clean Air for Europe nature and health targets, 3) N_2O by 50%, to contribute to national and international commitments for GHG emissions. In addition we will focus on three contrasting solution scenarios:

i) New production chains with more efficient use and recycling of N,
ii) Geographically differentiated N-measures based on intelligent planning and management of agricultural landscapes, and
iii) Changed consumption patterns driving land use change and reducing N use.

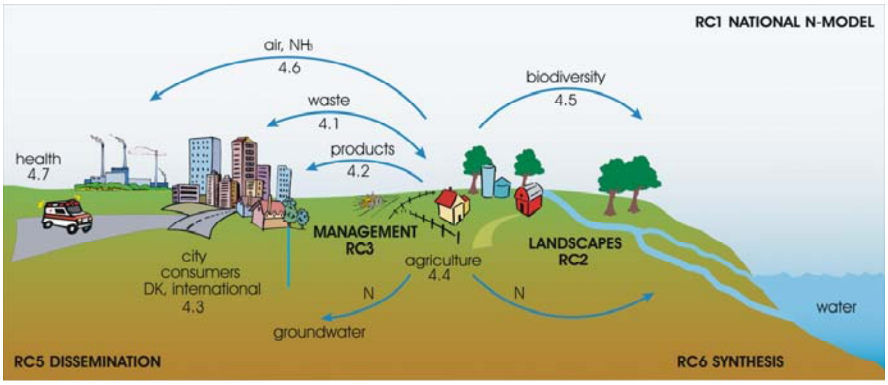

Fig. 1. Focus areas for the DNMARK Research Components RC1- RC6.

Methodology and results

As illustrated in Figure 1, the development of methodologies for sustainable N management will be divided into the five Research Components (RC1-RC5), and a coordination and synthesis component (RC6).

RC1 National N-model: In this component a national Danish N model (inputs, outputs and losses) for the period 1990-2010 is constructed. The model will quantify all major terrestrial and aquatic flows (Leip 2011) using the top-down method developed during the European N Assessment. The model will subsequently be refined in response to stakeholder comments and the consequences of solution scenarios. Subsequently, an alternative national scale model for the agricultural sector will be developed using a bottom-up approach based on farm-scale data and an existing farm N model (Happe et al., 2011), to allow a robust comparison with the top-down approach. Revised national N budgets for 1990-2010 and future national N budgets reflecting the consequences of solution scenarios will be included in the Danish N Assessment (RC6).

RC2 DNMARK Landscapes: In collaboration with local municipalities and farmers' unions case landscapes/ watersheds with both low and high NO_3^- retention are inventoried with farm and landscape data in GIS (Dalgaard et al. 2011b). A detailed N budget is constructed using inputs from RC1 and more detailed local data. Local scenarios for the case landscapes are formulated where N reduction effects of various changes in landscape, agricultural practice and technical installations are modelled. Forecasting scenarios allow the prediction of effects of changes on open trajectories, whereas backcasting scenarios allow optimization of landscape and farm management tools with fixed aims in terms of N loss reduction (Bende-Michl et al., 2011). The scenarios are formulated with stakeholders and in an iterative process with RC3, RC4.1-4.7 and RC5, ensured by a sequence of scenario-building followed by local workshops. In the last part of the RC we will evaluate the extent of other externalities brought about by the various N mitigation efforts. Selected ecosystem services (wildlife habitats, flood control, cultural heritage, recreation etc.) will be mapped in a baseline scenario, and the development in the provision of services will be assessed for additional scenarios (Andersen et al. 2013). The assessment will require development of new methodologies, in close collaboration with municipal stakeholders, and include assessments of the global effect of local land use change.

RC3 Management strategies: Scenarios for cost-effective N reductions to allowable loads for freshwater and marine waters will be formulated with input data from RC1 and RC2. Furthermore, cost-effective spatial distribution of measures to achieve the N load reductions will be modelled by applying existing cost minimization models at national level and at pilot study catchment level or larger ares as for instance Limfjorden catchment (Konrad et al. 2012). A comprehensive spatial model framework is developed to study alternative regulatory mechanisms (subsidies, taxes, quotas, spatial zoning, production or environmental legislation), modelling farm behavior as individual optimizing firms (Hansen & Hansen 2012). The model outcomes will be tested and refined using experimental data (Beharry-Borg et al. 2012) to test the extent to which the model output mimics behavioural outcome using alternative economic assumptions and approaches. Finally, the studies include implementation of measures that require cooperation between agents, as their effectiveness is dependent on scale and spatial adjacency. Spatially defined subsidy schemes and agglomeration bonus schemes will be investigated in a Payment for Ecosystem Services (PES) modelling framework. There will be special focus on construction of wetlands, buffer strips and watercourse maintenance, which needs collaboration between farmers at subcatchment level. We will use a heuristic optimization approach building on agent-based modelling frameworks (Touza et al. 2012). Promising PES schemes are evaluated using experiments in workshops (Beharry-Borg et al. 2012) where farmers evaluate the potential for implementing such schemes in the agri-environmental policy mix. The result will be compared to results from real cases where such payment schemes have been implemented, e.g. the Swiss example where farmers receive bonus payments when their fields are part of habitat networks (Wätzold et al. 2011).

RC4 Critical N impact issues: This RC focuses on gaps in our current N knowledge, and comprises in-depth studies of critical N issues in relation to a sustainable agriculture and food production. These issues have been identified by the alliance partners as of key importance to the quantification of N flows or to the mitigation of N losses in DK, and were also prioritized in the European N Assessment report as research needs. Moreover, each of these research education projects adds to the core competences of the research alliance members supervising the projects:

4.1 Urban-rural N recycling from waste: There is scope for increased recycling of N in urban waste residuals (WR) from new emerging technologies for municipal solid waste and waste water treatment, e.g. biosolids, composts, struvite precipitates, digestate (Svirejeva 2011). We will screen a range of WR together with the industry and for a subset quantify fertilizer value, improvement options, medium to long-term effects on soil quality and emissions (lab+field tests in long-term trials).

4.2 Cost benefits of N measures to improve surface water quality: The aim is to bridge costs analyses and benefit analyses in order to answers questions like: What is the optimal water quality in a given catchment from a cost-benefit viewpoint? How to proceed to cover the whole country, where local benefit analyses are not possible? How much can the costs of implementation be reduced if on site specific N-reduction potential can be obtained (Jensen et al. 2013).

4.3 Sustainable, low N food consumption: It is investigated whether the dual aims of reducing environmental N loss and reducing the protein share of healthy diets are congruent or conflicting, and on which scale. The work will estimate food demand component of the N map nationally and selected local areas, determine trends and drivers for consumption of Danish food products – nationally and internationally and analyse alternative interventions to change food demand behavior at the local level.

4.4a Watershed N Management: Managing N in more sustainable ways is an important and challenging task that must be synthesized by science and society in forms that are useful for policymakers, farmers and society in general. This involves bringing different disciplines and stakeholders together at different geographical scales, from national, watershed, landscape to local farm scale and with different stakeholder involvement processes in sustainable nitrogen management (Graversgaard et al. 2014). Going from farm to watershed based N management shows significant potentials for increased productivity combined with lower N-losses (Dalgaard et al. 2011b). Areas vulnerable to N-losses are selected from RC2, and new watershed management concepts are developed together with local stakeholders and farm advisory services. This local embedded type of knowledge when combined with biophysical knowledge of nitrogen and watershed processes is important to identifying new and more geographical targeted solutions to environmental problems (Voinov & Gaddis 2008). The aim of this RC 4.4a is to involve multiple stakeholders at multiple scales in the management of N and for this new sustainable N management models and participatory concepts shall be developed. Through a series of scenario workshops, in different test watersheds, an N -bio-physical model will be integrated with inputs from stakeholders to further enhance the resource effectiveness of N usage. The project will identify the potentials for developing a fully integrated socio-biophysical model.

4.4b Assessing Spatially Differentiated Nitrogen Mitigation in Agriculture: Developing and implementing a new, targeted and differentiated regulation of agricultural use of nitrogen (Natur- og Landbrugskommissionen 2013), and improved management of N in agriculture is seen as necessary to achieve a sustainable balance between the production of food and other biomass, and the unwanted effects of N on water pollution (Dalgaard et al. 2012). According to Article 16, EC Regulation, No.746/96 all EU member states are obliged to monitor and evaluate the environmental, agricultural, and socio-economic impacts of their agro-environment programs. Therefore in order to provide policy makers with the necessary information for responsible political action, research on the possible environmental and economic impacts of different N-mitigation strategies and regulation in catchment scale is essential. Thus the aim is to develop methodologies for spatial estimation of N-leaching for different mitigation options in Denmark and Baltic Sea region. This will be based on a review study of existing N mitigation options, land use and land management scenarios. Assessment of the spatially differentiated N measures will be done by comparison of different methods to estimate N leaching. Ecological and economic efficiency of spatially differentiated measures will be assessed through set up spatially differentiated scenarios of N management for selected catchment.

4.5 N mitigation, Ecosystems Services mapping and biodiversity management: Ecosystem services are in this context a way of understanding the ecological resources in the landscape and clarify the important processes and products we depend on from a functional nature (e.g., wastewater treatment, recreation opportunities and food production) (Turner et al., in prep.) The intensive land use, combined with high nitrogen emissions have a heavy impact on nature, and affect the functionality of ecosystem services (Tilman et al 2002). We focus on how composition and distribution of ecosystem services (ES) correlates with, among others, N mitigation options, N vulnerable areas, and agricultural production, to quantify synergy effects between N mitigation and biodiversity protection (Dise 2011). Spatial distributions of the proposed ES and N management are analysed, and based on among others the method of Turner et al. (2014) compared to the effects in different scenarios.

4.6 Agricultural airborne N-pollution, particle pollution and public health effects: The aim is to assess the contribution from agricultural N-emissions to negative health effects from ambient air particle exposure of the Danish population. This will be based on state-of-the-art source apportionments and exposure assessment will be used as basis for an epidemiological study with health register data, using a GIS approach. The integrated system approach, based on impact-pathway will be adjusted to assess the health-related economic externalities of agricultural air pollution (Brandt et al. 2011) based on a refined DNMARK dataset.

4.7 Groundwater N-pollution and public health effects: The aim is to assess the contribution from N polluted groundwater to negative health effects on the Danish population. This will be based on an epidemiological study of people exposed to nitrate containing drinking water and assess the incidence of cancer (e.g. colon cancers; van Grinsven et al. 2010) by combining drinking water quality data (Hansen et al. 2011) with health register data using a GIS approach.

RC5 Stakeholder involvement and dissemination: Local dissemination of the DNMARK results and solution scenarios will be developed and tested in the local landscapes and local farmer groups will meet on planned farm meetings, where the agenda is to identify measures at farm level that might improve resource efficiency and climate change adaptation, including C and N footprint. Through the utilisation of cognitive mapping, and the facilitation of learning processes between the multiple stakeholders at local development workshops, action plans for sustainable N-management strategies at local and regional level will be produced, and successful results will be disseminated through the national advisory services.

RC6 Management and synthesis: Annual solution scenarios workshops are used to facilitate stakeholder integration and crosscutting research and dissemination activities. The general solution scenario pathways are defined during the inception phase (yr 0) and form the basis for the work in RC1-RC5. The national scale baseline and preliminary scenario results (yr1) feed into more specific landscape scenarios (yr 2), management mitigation options to be quantified and discussed in yr 3, and the effects of the RC4 specific key N-topics to be synthesized in yr 4. These workshops and the specified RC deliveries ensure that results feedback to the final yr 5 synthesis scenarios to be developed both at landscape and national scales in the final DNMARK assessment, and the continuous dissemination of results (Figure 2).

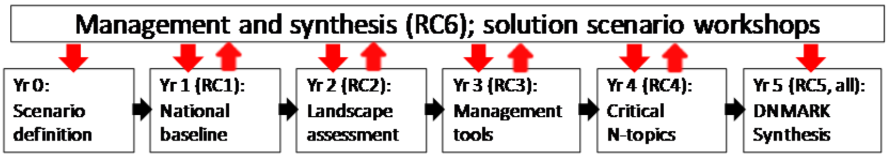

Fig. 2. Development of solution scenarios during the series of annual project meetings organized by RC6 as a cross cutting activity for stakeholder involvement, research activity coordination, and dissemination of results (co-organised by the RC's mentioned in brackets).

Examples of results and relevance to stakeholders

Table 1. Main DNMARK results and relevance to selected private and public stakeholders.

Output	Relevance to stakeholders
Solution scenarios to increased N efficiency, and significantly reduced N-footprint	It is recognized by Danish agriculture and major agribusinesses that significant improvements in N utilisation is crucial for the further development of the sector. The Danish government needs to comply with EU directives and international treaties, and development of a targeted strategy to reduce N-pollution is demanded.
The first full, dynamic model for N flows in	It is attractive for international research institutions to test new N-models in Denmark, and develop world leading agro-environmental

Denmark	databases. This is also important for documenting effects of national N-mitigation initiatives.
Landscape platforms to test effects of local N mitigation initiatives	Locally adapted N-mitigation solutions are important to municipalities' mandatory spatial planning and sustainable development strategies. New planning tools are needed, to integrate the full range of ecosystems services and the comparative, often disparate, advantages for local agribusinesses and rural development.
Models to assess cost-effectiveness of targeted and voluntary N measures	The societal costs of Danish N pollution amounts to billions of DKK yr^{-1} (Brink et al. 2011), and cost-effectiveness analyses and modeling of N measures are of high priority to the Danish Government. Especially the development of models for more efficient, location-specific instruments, including voluntary actions and improved collaboration between agents, is required to develop the bioeconomy.
New insights from post-docs and PhD studies in high-impact N topics	High-priority areas for further N research include the development of new urban-rural N recycling technologies, water policy cost-benefit analyses, sustainable food consumption and healthy lifestyles, agricultural watershed management and optimal N use, Ecosystem Services Assessment, and public health effects of air and water N pollution.
Dissemination and synthesis of knowledge	Via significant investments the Danish farm advisory services and agroindustry intend to integrate project results into new, more holistic local advisory services for the sustainable development of farming and food production in Denmark.

Concluding summary

Agricultural food and biomass production are the main sources of reactive nitrogen (N) pollution, causing N concentrations in air and water exceeding critical levels for eutrophication, significant greenhouse gas emissions, landscape and biodiversity deterioration, and severe human health impairments. In parallel, N is the main limiting factor to increased agricultural productivity. Many research-based N mitigation measures have already been implemented in Danish agriculture, yet N pollution and the related costs for society and the food sector remain unacceptably high. Future societal development will require N pollution to be significantly reduced while increasing the food and biomass production. Thus, innovative, cross-sectoral solutions to reduce N losses and ally public and private stakeholders are crucial for the development of a sustainable biobased economy. The DNMARK cross-disciplinary research alliance will identify barriers and develop research-based solutions to meet this N challenges, emphasising both costs and benefits of different development pathways. In an integrated project with core private and public partners we will focus on three main solution scenarios: i) New production chains with a more efficient use and recycling of N, ii) Geographically differentiated N-measures based on intelligent planning and management of agricultural landscapes, and iii) Changed consumption patterns driving land use change and reducing N use. For the first time, a consistent Danish framework for N flows will be set up, along with landscape study sites and economic evaluation models. PhD research studies will focus on critical N issues of relevance to the participating private and public stakeholders, and the project management and dissemination activities will ensure the results are synthesized and disseminated nationally and internationally. With the Danish N Mitigation Assessment (DNMARK), we aim to develop Denmark's international position in this area, and bring together Danish research environments, dealing with the N problem in the production and consumption chains of food and bioenergy. More than 20 public and private stakeholder partners and key international partners are actively involved, and will contribute to the fruitful process of building the alliance and creating innovative research. For more information see www.dnmark.org.

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