A nitrogen budget for Denmark; developments between 1990 and 2010, and prospects for the future

N J Hutchings\textsuperscript{1}, O-K Nielsen\textsuperscript{2}, T Dalgaard\textsuperscript{1}, M H Mikkelsen\textsuperscript{2}, C D Børgesen\textsuperscript{1}, M Thomsen\textsuperscript{2}, T Ellermann\textsuperscript{2}, A L Højberg\textsuperscript{3}, L Mogensen\textsuperscript{1} and M Winther\textsuperscript{2}

\textsuperscript{1} Department of Agroecology, Aarhus University, Blichers Allé 20, DK-8830 Tjele, Denmark
\textsuperscript{2} Department of Environmental Sciences, Aarhus University, Frederiksborgvej 399, DK-4000 Roskilde, Denmark
\textsuperscript{3} Geological Survey of Denmark and Greenland—GEUS, Øster Voldgade 10, DK-1350 København K, Denmark

E-mail: Nick.Hutchings@agro.au.dk

Received 31 July 2014, revised 16 October 2014
Accepted for publication 17 October 2014
Published 26 November 2014

Abstract

A nitrogen (N) budget for Denmark has been developed for the years 1990 to 2010, describing the inputs and outputs at the national scale and the internal flows between relevant sectors of the economy. Satisfactorily closing the N budgets for some sectors of the economy was not possible, due to missing or contradictory information. The budgets were nevertheless considered sufficiently reliable to quantify the major flows. Agriculture was responsible for the majority of inputs, though fisheries and energy generation also made significant contributions. Agriculture was the main source of N input to the aquatic environment, whereas agriculture, energy generation and transport all contributed to emissions of reactive N gases to the atmosphere. Significant reductions in inputs of reactive N have been achieved during the 20 years, mainly by restricting the use of N for crop production and improving livestock feeding. This reduction has helped reduce nitrate leaching by about half. Measures to limit ammonia emissions from agriculture and mono-nitrogen oxides (NO\textsubscript{x}) emissions from energy generation and transport, has reduced gaseous emissions of reactive N. Much N flows through the food and feed processing industries and there is a cascade of N through the consumer to solid and liquid waste management systems. The budget was used to frame a discussion of the potential for further reductions in losses of reactive N to the environment. These will include increasing the recycling of N between economic sectors, increasing the need for the assessment of knock-on effects of interventions within the context of the national N cycle.

Online supplementary data available from stacks.iop.org/ERL/9/115012/mmedia

Keywords: national, budget, balance, nitrogen

1. Introduction

The benefits of reactive nitrogen (N) for food production and industrial products, and the threat posed to human and ecosystem health by losses of reactive nitrogen were well described in the European Nitrogen Assessment (Sutton et al 2011). At the European scale, an economic assessment has suggested that the balance between cost and benefits is
not optimal and that further action is necessary to redress the balance (van Grinsven et al 2013). Over the past 25 years, Denmark has introduced increasingly stringent environmental legislation to curb emissions of ammonia (NH$_3$) and NO$_x$, and losses of nitrate (NO$_3^-$) by leaching. The national legislation often exceeds (and in some cases predates) international agreements and legislation such as the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) (UNECE 1979) and the European Union Nitrates Directive (EU 1991). The major sources of the N pollution have been agriculture (NH$_3$ and NO$_3^-$), energy production and transport (NO$_x$). Measures with the least cost have been implemented and future progress will be achieved at an increasing marginal cost. It is therefore worthwhile investigating other economic sectors to identify opportunities for increasing the efficiency of use of reactive N and reducing N losses.

The construction of partial N budgets for particular sectors such as agriculture (Parris 1998) or at the national scale (Slak et al 1998) is considered a useful way to identify major imbalances between the input and output of N at a range of scales. Fleckesder (1992) proposed using national N budgets as an aid to policymaking but the idea has lain dormant until recently, when Leip et al (2011) suggested that such budgets would be a valuable tool in resource optimization, not least as a policy tool for identifying opportunities for intervention. There are indications that this suggestion is being adopted (Junker 2013). Wier and Hasler (1999) developed a national terrestrial/aquatic/atmospheric N budget for Denmark for a single period in the late 1980s. Here, we report a first attempt at constructing a national N budget for Denmark for the years 1990 to 2010 and then use it as a framework for discussing opportunities for achieving a further reduction in losses of reactive N.

2. Methods

The sources of data used for the construction of the Danish N budget are documented in detail in the supplementary material, available at stacks.iop.org/ERL/9/115012/mmedia. Data on the mass flows of commodities are primarily collated from the statistical data held by Statistics Denmark. Data concerning losses of N species to the environment were collated from reports prepared to document Denmark’s compliance with the United Nations Framework Convention on Climate Change and the United Nations Convention on Long-Range Transboundary Air Pollution UNECE (1979), supplemented by reports prepared to support national policy-making. The following major pools involved in the N budget of Denmark were identified:

- Agriculture, with subdivision into livestock and crop production.
- Fisheries.
- Forestry and semi-natural areas.
- Food and feed processing industries.
- Consumers and urban areas.
- Solid waste management (refuse).
- Wastewater treatment.
- Industry.
- Energy production.
- Transport.
- Aquatic environment.
- Atmospheric environment.

The N concentrations in commodities were obtained from a wide range of sources. Where possible, data was collated for all years; where not, effort was made to collate data at five yearly intervals. Where data were missing, values were extrapolated from other years. In a number of cases, it was not possible to satisfactorily close the budget, either because data were not available or because there was a conflict between different data sources. Where these cases involved significant N flows, they are identified and discussed below. The data sources are detailed in the supplementary material.

3. Results and discussion

3.1. Methodological issues

Assessing the flow of N in feed to ruminant livestock proved problematic. The statistics concerning livestock feed are the sum of imported and domestically-produced feedstuffs. The statistics concerning feed imports can be considered reliable. The statistics covering domestic crop production are for grain and other crop products sold are based on documented material flows, whereas for roughage crops, production is based on estimates made by agricultural advisors. The latter accounts for 40–50% of the total N harvested in crops and a larger proportion of the animal feed, so the statistics concerning this major N flow are largely based on expert judgment. Using the official statistics for N in crop products used for animal feed and subtracting the N exported in animal products or estimated to be lost by gaseous emission from the manure management system, yields an estimate of N applied to land in animal manure. These estimates proved to be on average 24% higher than the official values used when estimating field emissions of NH$_3$ and N$_2$O, and the leaching of NO$_3^-$. The official manure application values are calculated from a survey of commercial feed rations, the statistics on the production of animal products, and estimates of N lost by gaseous emission from the manure management system. The method used to calculate the official manure application values was considered the more robust, so the consumption of N in animal feed was estimated here as the sum of the N applied in manure and the gaseous N losses. The official crop production statistics were nevertheless used for calculating N flows associated with crop and soil, since no alternative was available. Since the change in soil N was calculated as the difference between the inputs and outputs/losses, this means that errors in the estimate of crop production will propagate to this item. Note that for the N input in crop products to Food/feed processing, the estimates of Vinthor and Olsen (2013)
were used, since they identified the net export of crop products from agriculture.

Estimating the N produced as roughage feed for ruminant livestock is a recurrent problem when constructing N budgets for ruminant livestock farming, e.g. when calculating gross N balances using the method recommended by OECD (Par- 
ris 1998). Representative field surveying would be difficult and expensive and expert judgement represents a poor sub-
stitute for objective data, while basing roughage crop pro-
duction on a survey of commercial feeding practices would be
more reliable. Livestock farming will be a key source of greenhouse gas emissions for most countries, so they should be using the IPCC Tier 2 methodology (IPCC 2006) or a Tier 3 methodology for estimating N intake for ruminant livestock. This requires an estimate of the energy and N content of liv-
estock rations, so representative feed rations should be available.

Estimating the N flow in food/feed processing and waste streams proved difficult. It was not possible to satisfactorily close the N budget for food/feed processing, with the differ-
ence between the N input and output varying between −9% and 20% of the amount input. The difference between the amount estimated to be input to the sewage system by con-
sumers and the amount estimated to enter waste water treat-
ment plants averaged 25% of the former. In contrast, for waste water treatment plants and solid refuse treatment, the amount estimated to be output exceeded the amount input by averages of 27% and 25% respectively. The N flows within and between the agricultural and aquatic ecosystems has been a focus of much research in Denmark over the last 20 years, due to the political attention given to \( \text{NO}_3^- \) leaching. In contrast, nutrient flows within sectors dealing with food waste and waste management have only recently received political attention and this is reflected in the quality of the statistical information available; the quality and detail of the data collected and collated at the national scale depends primarily on the demand for information from policymakers.

Since the questions of interest to policymakers change with time, together with the resources available and meth-
odologies used, it will always be difficult to obtain complete and consistent data for a 20 year period. Furthermore, data are usually collected on a sector by sector basis, sometimes creating difficulties quantifying inter-sectorial material flows. If a national N budget for Denmark is to be of value for policy-making or informing the public debate, further work is required to resolve some of the difficulties found in this work. Since the exercise undertaken here exclusively accessed information publicly available via the Internet, some of which was sparsely documented, it is likely that many of the issues can be resolved by reference to information only available on paper or by interacting with the data providers.

3.2. National budget

The national N budgets for Denmark in 1990 and 2010 are shown in figure 1. Note that to reduce clutter, a number of minor flows have been omitted. Detailed figures and data, including flows for intermediate years, are presented in the

...
Figure 1. Nitrogen budgets for Denmark in 1990 and 2010; all flows are in kt N yr$^{-1}$. 
due to the different periods, partly because limitations in some statistical information leave scope for different interpretations.

The N flows into, within and out of a country would be expected to vary according to a number of factors; the area and quality of land influences the agricultural production and the human population influences the proportion of that production consumed domestically and the importance of non-agricultural activities. Globally, the level of economic development is likely to affect the proportion of the population living in urban areas and the consumption of animal products. Of the national N budgets currently available, the budget for The Netherlands published in Leip et al (2011) is the one with which it is most appropriate to compare the results of this study; a Western European country with an intensive agricultural industry. The data in Leip et al (2011) is for The Netherlands in the 1990s. In this period, the similarities with Denmark for the same period are the large flow of N in fertilizer and animal feed, and the losses of reactive N gases. The main differences are that for the case of The Netherlands, the manure production was higher, the use of industrial and agricultural products by consumers was higher, the leaching of NO$\text{$_3$}^-$ from agriculture was lower and the loss of N$_2$ from agriculture much higher. The manure production appears to be particularly high, considering that the agricultural area was about one third of that of the Danish, reflecting the importance and intensity of the livestock sector in The Netherlands at that time. The difference in consumption of agricultural products can be explained by the difference in population; consumption was estimated to be about 7.9 and 6.7 kg N capita$^{-1}$ yr$^{-1}$ for The Netherlands and Denmark respectively. In contrast, the consumption of 20 kg N capita$^{-1}$ yr$^{-1}$ of non-food commodities in The Netherlands is difficult to explain and requires further investigation. The NO$\text{$_3$}^-$ N leaching in The Netherlands was equivalent to about 46 kg N (ha agricultural area)$^{-1}$ yr$^{-1}$, which is about half that of Denmark at the time (about 93 kg N (ha agricultural area)$^{-1}$ yr$^{-1}$). Conversely, the loss of N$_2$ of 210 kg N (ha agricultural area)$^{-1}$ yr$^{-1}$ in The Netherlands was much higher than in Denmark (28 kg N (ha agricultural area)$^{-1}$ yr$^{-1}$). In much of The Netherlands, the water table is close to the surface of agricultural land, which leads to high emissions via denitrification and a consequent reduction in the proportion of NO$\text{$_3$}^-$ created that remains for leaching. In contrast, the water table is much lower in most of Denmark, so denitrification is lower and a greater proportion of the NO$\text{$_3$}^-$ created remains for leaching. Substantial losses of N$_2$ via denitrification of agricultural NO$\text{$_3$}^-$ also occur in Denmark but are here attributed to the aquatic environment rather than agriculture.

3.4. Technical measures to reduce harmful N losses to the environment

3.4.1. Agriculture. Inputs in the form of fertilizer and animal feed to support agricultural production are responsible for much of the N that drives harmful losses, particularly NO$\text{$_3$}^-$ leaching and emissions of NH$_3$ and N$_2$O. However, driven by a combination of legislation and economic advantage, Danish farmers have already achieved substantial reductions in N losses, through improved animal and crop husbandry (Dalgaard et al 2014). This combination seems likely to maintain the reductions achieved, even in the face of moderate changes in the market (e.g. the removal of milk quotas). On the other hand, the least cost (and sometimes negative cost) measures are largely already implemented, so further improvements will be challenging.

A number of additional measures are currently being implemented. Restrictions on NH$_3$ emissions and the enforced N fertilization of crops to 15–20% below the economic optimum are together encouraging farmers to employ low NH$_3$ emission technology. The aim of the Danish government is to double the area farmed organically by 2020, from the current value of about 7% of the agricultural area. If successful, this may reduce N losses, since the N surplus for Danish organic farms appears to be lower than for conventional farming (Dalgaard et al 1998). As part of its future energy strategy (Danish Ministry of Climate, Energy and Building 2012), the Danish government has a target of anaerobically digesting 50% of animal manure by 2020 and although the primary objective of the policy is the reduction in fossil fuel usage, a side-effect is that the mineralization of manure organic N will improve the efficiency with which it can be used for fertilization. Under Danish nutrient legislation, this will result in a further reduction of mineral fertilizer use. Following the report of a commission on agriculture and nature (Nature and Agriculture Commission 2013) and in response to the EU Water Framework Directive (EU 2000), a second measure under development is to require land that is particularly susceptible to NO$\text{$_3$}^-$ leaching to be used for crops that require little N fertilization or have the ability to retain a high proportion of N applied (e.g. woody perennials for energy production), or to be taken out of agricultural production completely. At present, it appears that the value of energy crops is too low and the price of land too high for this to be economically feasible for implementation over large areas. In some locations, it may be feasible to intercept leached NO$\text{$_3$}^-$ before it can enter watercourses, either by creating artificial wetlands (although the focus of the latter is currently removal of P rather N) or by growing, harvesting and removing an under-fertilized perennial crop such as grass. The latter option is feasible if there is a local recipient for the grass, such as a ruminant livestock farm, and the quality of the grass is suitable. In the longer term, it is possible that the development of a biorefinery capacity will create an additional market for such material and provide an additional route for recycling N.

3.4.2. Transport and energy. The opportunities for further reducing the NO$\text{$_3$}$ emissions from transport and energy via abatement technologies are limited, since much has already been achieved. However, changing to electricity as the source of power would reduce NO$\text{$_x$}$ emissions, provided the electricity were generated using a method that did not itself lead to higher NO$\text{$_x$}$ emissions (e.g. hydroelectric, solar, wind).
3.4.3. Food/feed processing. Significant steps have already been taken to minimize the waste from food and feed processing. Carcass parts of slaughtered livestock not commonly consumed in western cultures are marketed in the Far East or converted into feed for pets or fur animals. Readily-degradable carcass fractions such as the gut contents are also used as feedstock for biogas generation or for biofuel production, while other fractions are used as organic fertilizer. The potential for further efficiencies appears limited here. However, there remains scope for reducing the food waste from retailers, from restaurants and in institutional food preparation (Mogensen et al 2013), and recycling that which remains.

3.4.4. Consumers, refuse and wastewater. Food waste by consumers remains a significant issue that can be tackled by education (Mogensen et al 2013). Food waste cannot be eliminated completely, since some foods are sold in forms that contain inedible components (e.g. citrus fruit peel, bones). Reducing food waste would not reduce N losses unless it resulted in reduced the amount of food purchased. If the effect were to be to increase consumption, the N would be partitioned to wastewater as excreta rather than solid domestic refuse. At the national scale, a reduction in food purchases would probably result in lower imports of food not produced in Denmark and higher exports of those that are.

Most of the N in refuse is contained in food or garden waste. At present, much of Danish refuse is used for energy generation, without separation. Significant progress can therefore be made towards recycling the N via composting or anaerobic digestion and the government has established targets for substantially increasing the recycling of organic waste by these means (Danish Ministry of the Environment 2013).

Most domestic sewage and much industrial sludges are already recycled as organic manures to agriculture. However, the choice of aerobic treatment followed by denitrification means that most of the N entering wastewater treatment plants is lost to the atmosphere as N₂, rather than being recycled. In the future, it would be preferable if this N were to be captured, reprocessed and recycled (Oenema et al 2011).

3.5. Strategic measures

One of the major ecological impacts of reactive N is the eutrophication of seminatural ecosystems. In terrestrial seminatural ecosystems, deposition of N leads to unwanted changes in plant species composition whereas in coastal waters, it is a major contributor to algal blooms and subsequent anoxia. For Denmark, N deposition resulting from domestic reactive N emissions only accounts for about 33% of deposition to land and 12% of deposition to coastal waters, the remainder coming from other countries (Jensen et al 2012). At the same time, Denmark has at significant cost implemented some of Europe’s most stringent measures to limit NH₃ and NO₃ emissions. Denmark therefore has a strong ecological and economic interest in pressing neighboring countries to commit to ambitious N emission reductions and subsequently monitoring compliance with these commitments.

Two initiatives currently on the policy horizon could have a significant impact on N flows Danish crop production in the longer term. The development of a substantial biorefinery capacity (Jørgensen 2014), aimed at replacing industrial feedstocks currently provided from fossil materials, could lead to a significant extension in the area planted to perennial crops. Protein-rich byproducts from biorefineries could provide an alternative to imported protein-rich feeds such as soya. However, under existing nutrient management legislation, a switch from annual to perennial cropping would result in an increase in the amount of plant-available N per hectare that could be applied to the land cropped in this way. The second development that could impact Danish crop production would be the development of biomass production for energy generation (Jørgensen et al 2013). In contrast to crop production for biorefineries, energy crops tend to have a moderate to high ability to retain N; moderate for crop silage, high for perennials such as willow coppice and Miscanthus spp.

Livestock farming has been particularly associated with high losses of reactive N (Leip et al 2014), leading to a suggestion that measures to reduce the amount of animal protein in human diets would be beneficial (Reay et al 2011). Refocussing agriculture away from livestock production and towards crop production has also been suggested as a means of increasing the global availability of protein for human consumption (Aiking 2014). This may be true if livestock are only fed crop products not suitable for human consumption (Fairlie 2010). This may be true from a global perspective but from a purely Danish perspective, the environmental effect of such a change in domestic consumption patterns is likely to be limited since any reduction would probably result in increased exports.

The direct impact of any policy-driven change in Danish food production on global food supply will be limited. Denmark accounts for respectively about 0.2, 1.5 and 0.8% of global beef, pork and milk production (FAOSTATS). The contribution to food exports is greater; about 3.5, 5.1, and 2% of cow butter, cheese and other dairy products, 2.7% of beef and 9.7% of pork (FAOSTATS). In contrast, the direct impact of any policy-driven change in Danish food production on Denmark is potentially high; agriculture and food production accounts for 12% of Danish gross domestic product, employs 8.5% of the labor force and the export of agricultural and food products accounts for 12% of Danish exports (Danish Agriculture and Food Council 2014). Since the low-cost or negative-cost measures to reduce the circulation of reactive N have long since been implemented, it is useful to consider why the Danish government continues to take a positive approach to reducing this circulation. The first reason is domestic public pressure to limit the environmental damage caused by reactive N. As a consequence, the policy of the Ministry of Agriculture, Food and Fisheries is to balance the economic benefits and environmental costs of farming (Ministry of Agriculture, Food and Fisheries 2014). The second appears to be the belief that by imposing more...
stringent regulation, it will create a domestic market for environmental technologies, thereby encouraging research and development that will lead to the sale of equipment and expertise to other countries (Danish Energy Agency 2014). This strategy presupposes that there is a long-term global (or at least European) trend to restrict N emissions to the environment and that any short-term disadvantage to Danish agriculture can be offset by government subsidies. Whilst the latter is under the control of the Danish government, the former requires international acceptance of the need for further measures to reduce losses of reactive N. We believe that national N budgets provide an informative and persuasive method of convincing both public and politicians of the need to continue this momentum.

3.6. Value of a national approach

The prominence of agriculture in national N budgets is a common feature in the studies available (Leip et al. 2011). The prominence of agriculture in Denmark and the magnitude of the N flows into, out of and within the sector has meant and will continue to mean that significant progress in reducing the losses of reactive N to the environment can be made by considering this sector alone. The value of taking a national, multi-sectoral approach, beyond that of the educational value, has to be argued in terms of achieving a more cost-effective reduction by taking a holistic approach and gaining an understanding of the flows between sectors. The benefits of a cross-sectoral approach are already proven in Denmark, by the work of agricultural, atmospheric and hydrological scientists to assess the contribution of different sources to the input of N to coastal waters.

4. Conclusions

Identifying, quantifying and understanding the flows of N between different sectors helps identify opportunities for increasing the efficiency of use of reactive N and reducing overall losses to the environment. In Denmark, much progress has been made in the absence of a national N budget, not least because the focus on NO3− leaching has demanded the use of a cross-sectoral approach. Strategies designed to achieve further reductions in losses of reactive N are likely to include increased recycling of N between economic sectors, increasing the need for the assessment of knock-on effects of interventions within the context of the national N cycle.

The development of national N budgets will be a useful method for disseminating knowledge of flows of reactive N outside the scientific community.

Acknowledgements

This work has been supported by the www.dnmark.org Strategic Research Alliance DNMARK: Danish Nitrogen Mitigation Assessment: Research and Know-how for a sustainable, low-Nitrogen food production (2013–2017) funded by The Danish Council for Strategic Research (reference 12-132421) and the Aarhus University Research Foundation.

References

Aiking H 2014 Protein production: planet, profit, plus people? Am. J. Clin. Nutr. 100 4835–98
Dalgaard T, Halberg N and Kristensen I S 1998 Can organic farming help to reduce N-losses? Experiences from Denmark Nutr. Cycling Agroecosyst. 52 277–87
Dalgaard T, Hansen B, Hasler B, Hertel O, Hutchings N J, Jacobsen B H, Kronvang B, Olesen J E, Schjørring J K and Vejre H 2014 Policies for agricultural nitrogen management—trends, challenges and prospects for improved efficiency in the case of Denmark Environ. Res. Lett. 9 115002
Danish Agriculture and Food Council 2014 (www. agricultureandfood.co.uk/Statistics/ The_Danish_agricultural_industry.aspx) Accessed October 2014
Danish Energy Agency 2014 Green Production in Denmark—its Significance for the Danish Economy (Copenhagen: Danish Energy Agency) p 56 (www.ens.dk/sites/ens.dk/files/policy/ green-production-denmark-contributes-significantly-danish-economy/Green%20production%20n%20Denmark%20-%20web%20111212.pdf)
Danish Ministry of Climate, Energy and Building 2012 Accelerating green energy towards 2020 Available at (www.ens.dk/en/info/publications/accelerating-green-energy-towards-2020)
Danish Ministry of the Environment 2013 Denmark without waste Available at (www.denmark-uden-affald.dk)
EU 1991 Council Directive of 12 December 1991 Concerning the Protection of Waters Against Pollution Caused by Nitrates from Agricultural Sources Communities, C.o.I.E. (Ed.) (Official Journal of the European Communities) No L 375/1 Available at (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0676)
EU 2000 Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000, establishing a framework for Community action in the field of water policy (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32000L0060)
Fairlie S 2010 Meat, A Benign Extravagance (East Meon, UK: Permanent Publications)
FAOSTATS 2014 Production and export statistics, accessed October 2014
Fleckseder H 1992 A nitrogen balance for Austria Water Sci. Technol. 26 1789–95
IPCC 2006 Intergovernmental panel on climate change guidelines for national GHG inventories Available at (www.ipcc-nggip.iges.or.jp/public/2006gl/index.html)
Jensen P N et al 2012 Aquatic Environment and Nature 2011 (Aarhus: Aarhus University) p 102 Available at (http:// naturstyrelsen.dk/media/nst/06849_NOVANA_Vandmiljoe_Natur_2011.pdf)
Jørgensen H 2014 Current status on biorefineries in Denmark Available at (www.biorefinery.nl/fileadmin/biorefinery/docs/publications/presentations-kickoff/ _4__Country_status_Denmark_IE42_150307.pdf)
Jørgensen U et al 2013 Utilisation of Biomass in Denmark—Potential Resources and Sustainability (Aarhus: Aarhus University) Available at (http://web.agrsci.dk/djfpublikation/ djfpdf/dcarapport33.pdf)
Junker P 2013 Luxembourg’s integrated nitrogen budget 2010 and estimation of its nitrogen saving and recovery potentials MSi in Applied Environmental Economics, (University of London)
Leip A et al 2011 Integrating nitrogen fluxes at the european scale The European Nitrogen Assessment ed M A Sutton,
C M Howard, J W Erisman, G Billen, A Bleeker, P Grennfelt, H Grinsven and B Grizzetti (Cambridge: Cambridge University Press) pp 345–76

Leip A, Weiss F, Lesschen J P and Westhoek H 2014 The nitrogen footprint of food products in the European Union J. Agric. Sci. 1–14

Ministry of Agriculture, Food and Fisheries 2014 See translation of Ministry web page in supplementary material

Mogensen L, Hermansen J E and Knudsen M T 2013 Food Waste in the Food Sector—From Primary Production to the Consumer (Aarhus: Aarhus University) p 48

Nature and Agriculture Commission 2013 Nature and agriculture—a new start available at (www.naturoglandbrug.dk)

Oenema O et al 2011 Developing integrated approaches to nitrogen management European Nitrogen Assessment ed M A Sutton, C M Howard, J W Erisman, G Billen, A Bleeker, P Grennfelt, H Grinsven and B Grizzetti (Cambridge: Cambridge University Press) pp 541–50

Parris K 1998 Agricultural nutrient balances as agri-environmental indicators: an OECD perspective Environ. Pollut. 102 219–25

Reay D S et al 2011 Societal choice and communicating the European nitrogen challenge European Nitrogen Assessment ed M A Sutton, C M Howard, J W Erisman, G Billen, A Bleeker, P Grennfelt, H Grinsven and B Grizzetti (Cambridge: Cambridge University Press) pp 585–601

Slak M F, Commagncal L and Lucas S 1998 Feasibility of national nitrogen balances Environ. Pollut. 102 235–40

Sutton M A, Howard C M, Erisman J W, Billen G, Bleeker A, Grennfelt P, Grinsven H V and Grizzetti B 2011 European Nitrogen Assessment (Cambridge: Cambridge University Press)

UNECE 1979 Convention on long-range transboundary air pollution. Available at (www.unece.org/env/lrtap/)

van Grinsven H J M, Holland M, Jacobsen B H, Klimont Z, Sutton M A and Willems W J 2013 Costs and benefits of nitrogen for europe and implications for mitigation Environ. Sci. Technol. 47 3571–9

Vinther F P and Olsen P 2013 Nutrient Balances and Nutrient Surpluses in Agriculture (Aarhus: Aarhus University) 1991/92–2011/12 (in Danish)

Wier M and Hasler B 1999 Accounting for nitrogen in Denmark—a structural decomposition analysis Ecol. Econ. 30 317–31