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Quantification and comparison of subnational and national agricultural nitrogen flows in Denmark and Sweden

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Keywords: croplands, grasslands, livestock, nitrogen use efficiency, nitrous oxide, ammonia

Supplementary material for this article is available online

Abstract

Ensuring food production with low nitrogen (N) environmental emissions requires good quantitative knowledge of N flows in agricultural systems to monitor emissions and N use efficiency (NUE, the ratio of N outputs to inputs). Our study quantifies the main N agricultural flows at subnational and national scales in Denmark and Sweden from 2011 to 2020, calculating the NUE for crop and livestock production and associated nitrous oxide (N_2O) and ammonia (NH_3) emissions. In Denmark, our results indicate a similar use of organic (manure) and synthetic N fertilizers (230 and 213 kt N y^{-1}, 83 and 77 kg N ha^{-1} y^{-1}); in contrast, Sweden used more synthetic (162 kt N y^{-1}, 54 kg N ha^{-1} y^{-1}) than organic N (108 kt N y^{-1}, 36 kg N ha^{-1} y^{-1}), with subnational variation in manure use as determined by livestock population. Livestock feed N intake was twice as large in Denmark (384 kt N y^{-1}) as in Sweden (176 kt N y^{-1}), reflecting Denmark's larger livestock population. Denmark's national crop NUE was lower (0.51) than Sweden's (0.72), likely due to a lower proportion of grass–clover leys, higher N input rates, and more intensive production systems. However, considerable subnational variation existed in both countries. The livestock NUE was 0.29 in Denmark and 0.25 in Sweden; these differences are mainly due to a higher proportion of ruminants in Sweden with lower N feed use efficiency than pigs. Sweden emitted less N_2O and NH_3 per unit area (∼56% for both gases) and in total (∼52% for both gases) than Denmark due to lower use of N inputs and less intensive farming systems. West Denmark and South Sweden were identified as emission hotspots. Our research provides essential information at subnational and national scales to improve N management and reduce gaseous N pollution, supporting the transition towards more sustainable agroecosystems in Denmark and Sweden.

1. Introduction

Agriculture has disrupted the global nitrogen (N) cycle (Schulte-Uebbing *et al* 2022, Richardson *et al* 2023). Inputs of N, essential for crop and livestock production, have increased from 40 Tg N y^{-1} in 1960–161 Tg N y^{-1} in 2010 worldwide (Van der Hoek 1998, Zhang *et al* 2021). This rise has led to N losses to the atmosphere, such as ammonia (NH_3) and nitrous oxide (N_2O), and to water bodies as nitrate (NO_3^-) (Ascott *et al* 2017, Tian *et al* 2020, Vira *et al* 2020). On a global scale, agriculture accounts for 81% of NH_3 emissions (Van Damme *et al* 2021, Wyer *et al* 2022) and 52% of anthropogenic N_2O emissions (Tian *et al* 2020). These losses of N impair biosphere functioning and contribute to climate change, ozone depletion, eutrophication, biodiversity loss, and air pollution (Anderson *et al* 2003, Ravishankara *et al* 2009, Richardson *et al* 2023).

Improving nitrogen use efficiency (NUE), the ratio of N outputs to inputs, is essential for ensuring food production with reduced environmental N losses (Ren *et al* 2023, You *et al* 2023). The most common metrics to evaluate NUE of agricultural systems are at the crop (NUE_{crop}) and livestock ($NUE_{livestock}$) levels. NUE_{crop} considers N in crop products (including cropland and grassland) as outputs, while $NUE_{livestock}$ considers N in animal products such as milk and meat (Leip *et al* 2011, Congreves *et al* 2021). Developing and evaluating these metrics at subnational and national scales enable a better understanding of the diverse N flows they encompass (i.e. N inputs, N outputs, and N gaseous emissions). These insights can help identify and monitor key sources of N losses, providing crucial information to inform policies to reduce local and subnational N pollution while increasing NUE (You *et al* 2023).

European farming systems contribute substantially to gaseous N emissions, averaging 4.2 Tg NH_3–N y^{-1} and 0.15 Tg N_2O–N y^{-1} over recent decades and making the region a hotspot for such emissions (Tian *et al* 2020, Beaudor *et al* 2023). Relatively high NUE characterizes agriculture in North European countries such as Denmark and Sweden compared to others (Lassaletta *et al* 2014, 2016, Einarsson *et al* 2022). However, the crop and livestock production systems of both countries differ due to pedoclimatic and geographic conditions, historical heritage, and national regulations (Levers *et al* 2016, Hutchings *et al* 2020, de Vries *et al* 2021). Sweden is geographically one of the largest countries in Europe. Still, only c. 6.5% of Sweden's total land area is dedicated to agriculture (3.01 Mha for 2020), and a relatively large share of agricultural land is covered by moderately intensive systems with grass–clover leys and cereals as the dominant crops (Swedish Board of Agriculture 2020). In contrast, with more than 60% of the land used for agriculture (2.87 Mha for 2020), Denmark is in the top three countries in the world with the greatest share of agricultural land (cereals dominating the agricultural area) and is one of the largest pig-producing countries in the EU (Dalgaard *et al* 2014, Willems *et al* 2016). An example of regulatory differences of importance for NUE between countries is that application rates of N fertilizer are limited by law in Denmark but not in Sweden (Svanbäck *et al* 2019, Sommer and Knudsen 2021). These marked differences in agricultural land use underpin contrasting N flows in these neighboring countries. Examining the consequences of these differences for crop and livestock NUE can shed light on each country's performance for sustainable nutrient management.

Effective N policy actions are expected to be implemented and tailored to subnational scales (Kros *et al* 2018, Serra *et al* 2019), underscoring the need to evaluate N flows for more sustainable practices at a subnational level (e.g. Sanz-Cobena *et al* 2023). While national N balances and emission estimates are made by public authorities (Swedish Environmental Protection Agency 2024, Nielsen *et al* 2023) and researchers (e.g. Groenestein *et al* 2019, Einarsson *et al* 2022), detailed and up-to-date subnational quantification remains absent. These assessments at finer resolution are needed to devise spatially targeted measures to increase NUE and to identify subnational hotspots of N gaseous emissions, thus effectively informing N abatement strategies and policies.

In our study, we aim to quantify the essential N flows in the agricultural systems of Denmark and Sweden using subnational information. Specifically, we estimate agricultural N inputs and outputs at subnational and national scales from 2011 to 2020. We use this information to calculate NUE at crop and livestock levels and evaluate production performance. Additionally, we estimate direct emissions of NH_3 and N_2O using a Tier 2 approach, where possible.

2. Material and methods

2.1. System boundaries for nitrogen flows

Our analyses focused on the agricultural land, including cropland and grassland, in Denmark and Sweden, which averaged 2.78 and 3.03 Mha for 2011–2020, respectively. We quantified N inputs and outputs for agricultural land and livestock production.

2.1.1. Nitrogen use efficiency

NUE was defined as the ratio between N outputs and N inputs for agricultural land (NUE_{crop}) and livestock ($NUE_{livestock}$) (Karimi *et al* 2020). The N inputs for the agricultural land boundary were symbiotic N_2 fixation, atmospheric N deposition, and synthetic and organic N fertilizer. The N output was N in crop products from croplands and grasslands, including N intake by grazing livestock. The input for the livestock boundary was N in feed intake (including grazing) by livestock, and the outputs were the animal products, meat (carcass), eggs, and milk.

2.2. Nitrogen inputs

2.2.1. Symbiotic N_2 fixation

Symbiotic N_2 fixation was estimated from the production of symbiotically N_2-fixing crops and estimates of fixation rates relative to production (Anglade *et al* 2015). For mixtures of legume and non-legume species, the fixation estimate was based on the legume component of the production. In Denmark, the production quantities and area were obtained from Statistics Denmark (www.statbank.dk/), including pulses, lucerne, and grass–clover mixtures in rotation at a subnational scale. In Sweden, legume distribution in crop mixtures was based on data from Statistics Sweden (2021) and additional assumptions following Einarsson *et al* (2022).

2.2.2. Atmospheric N deposition

In Denmark, atmospheric N deposition data was sourced from NOVANA (Ellermann *et al* 2018) and extracted from the relevant reports (e.g. Ellermann *et al* 2020). The total N deposition was aggregated at a subnational scale. In Sweden, total N deposition was obtained from the agricultural N budgets provided by Statistics Sweden (2021).

2.2.3. Synthetic and organic fertilizers

We estimated the subnational application of synthetic and organic (manure) N fertilizers in Denmark using the Danish General Farm Register data. This database compiles the yearly use of synthetic N fertilizer at the farm level, defined by crop and soil type (e.g. Danish Agency for Agriculture 2020). It also includes N use from manure sources, calculated based on farm livestock census data, livestock type, and N-excretion coefficients provided by the National Center for Food and Agriculture (Børsting *et al* 2021). Additionally, the database includes other organic N inputs (e.g. sewage sludge) applied to agricultural lands. The information was aggregated from the farm level to the subnational scale.

In Sweden, subnational data on the application of synthetic N fertilizers were sourced from Statistics Sweden (2023), based on national surveys conducted every 2–3 years. Manure N application and grazing excreta were estimated using an N mass-balance model for livestock excretion, grazing, and manure management, following the Tier 2 model presented in the Swedish Informative Inventory Report (Swedish Environmental Protection Agency 2024). This model incorporates subnational livestock census data (Swedish Board of Agriculture 2024) and national parameters for N excretion coefficients, manure management systems, and gaseous emissions from the Swedish Informative Inventory Report (Swedish Environmental Protection Agency 2024). The manure model calculates the flow of livestock N excreta by animal type, dividing excreted N between grazing and manure management systems. Data on the application of N from sewage sludge were extracted from subnational agricultural N budgets established by Statistics Sweden (2021).

2.3. Nitrogen outputs

2.3.1. Crop production, plant residues, and N uptake

Crop product data and areas were obtained from Statistics Denmark (www.statbank.dk/) and Statistics Sweden (2021). We calculated the N removed with harvests and grazing using the N concentration values from Einarsson *et al* (2021). Biomass and N uptake in above- and below-ground residues were estimated using allometric relationships based on production and N concentration, as detailed in Nielsen *et al* (2023) for Denmark and the Swedish Environmental Protection Agency (2024) for Sweden.

2.3.2. Livestock population, products, N content, and feed intake

Subnational livestock populations (cattle, sheep, goats, pigs, and poultry) were obtained from the Farm Structure Survey of the Eurostat database (https://ec.europa.eu/eurostat) for Denmark and from census data (Swedish Board of Agriculture 2024) for Sweden. Livestock products (i.e. milk delivered to dairies, egg production, and slaughtered livestock) were obtained from Statistics Denmark (www.statbank.dk/) at a national scale and the Swedish Board of Agriculture (2024) at a subnational scale. Danish livestock products were downscaled to NUTS-2 level based on the proportion of livestock populations.

In both countries, we estimated the total N content in slaughtered livestock based on reported carcass weights and the distribution of N between carcass and non-carcass parts as compiled by Le Noë *et al* (2017). We used the N concentrations that Le Noë *et al* (2017) provided for milk and egg production to estimate the N outputs. We used a standard mass balance to estimate the N intake by livestock, assuming that feed N intake equals the sum of N in livestock products (milk, eggs, and carcass and non-carcass parts) and the N in manure ex-animal (Billen *et al* 2024).

2.4. Nitrous oxide emissions

Direct soil N_2O emissions from synthetic and organic (manure) N fertilizer applications and other sources (i.e. crop residues) were calculated using two methods in Denmark and one in Sweden. In Denmark, the first method used Tier 2 emission factors for annual periods (Petersen *et al* 2023a, 2023b). The second method followed similar reporting methods for national N_2O inventories, namely using IPCC Tier 1 emission factors considering temperate regions (Hergoualc'h *et al* 2019). Only the latter (IPCC Tier 1) method was used for Sweden.

We calculated N_2O emissions from manure management systems and grazing excreta using nationally specific methods. For Denmark, emissions from manure management were calculated using emission factors from Nielsen *et al* (2023) and activity data from the Danish General Farm Register data, including animal category information, manure type, and N in produced manure. N_2O emissions during grazing were calculated based on the types of animals and their yearly grazing time (Nielsen *et al* 2023) using Tier 2 emission factors (Børsting *et al* 2021). For Sweden, all these N_2O emissions were calculated using the N mass flow model described in section 2.2.3. The Tier 2 and Tier 1 emission factors for N_2O are detailed in the supplementary information (tables S1, S2 and S4).

2.5. Ammonia emissions

For Denmark, we calculated NH_3 emissions from animal housing and manure storage using data from the Danish General Farm Register, which includes information on the quantity and types of barns, animals, and manure. We applied Tier 2 emission factors for NH_3 emissions (Børsting *et al* 2021) and accounted for NH_3 reduction technologies (slurry acidification, slurry cooling, and heat exchangers) based on the proportion of stables and slurry incorporating such technologies from Nielsen *et al* (2024). The NH_3 emission during grazing was estimated using data on animal types and yearly grazing durations (Nielsen *et al* 2023), along with national Tier 2 emission factors (Børsting *et al* 2021, Nielsen *et al* 2023). We used the Tier 2 emission factors for NH_3 from Nielsen *et al* (2023) for N fertilizer application.

For Sweden, NH_3 emissions from animal housing, manure storage, and grazing were estimated using the Tier 2 N mass balance model described in section 2.2.3. The application of N manure and sludge was based on the Tier 2 model from the Swedish Informative Inventory Report (Swedish Environmental Protection Agency 2024). The NH_3 volatilization from synthetic N fertilizers was estimated using Tier 2 emission factors, considering Sweden's average mix of synthetic N fertilizer types (Swedish Environmental Protection Agency 2024). The Tier 2 emission factors for NH_3 are detailed in the supplementary information (tables S1–S4).

2.6. Data analysis

To compare the agricultural systems in Denmark and Sweden, we estimated the averaged N flows (i.e. inputs, outputs, and gaseous emissions) over the period (2011–2020) per agricultural land (kg N ha^{-1} y^{-1}) and in total amount in the agricultural land (kt N y^{-1}). The NUE_{crop} and $NUE_{livestock}$ were calculated at the subnational and national levels; a linear trend was fitted to the time series of the NUE metrics using linear regression. The spatial distribution of N flows at the subnational level was built based on the averaged values (kg N ha^{-1} y^{-1}) and using choropleth maps. Similarly, the bivariate choropleth maps of N_2O and NH_3 emissions at a subnational scale were built for the averaged values over the studied period (kg N ha^{-1} y^{-1}). Data processing, analysis, and figure generation were executed using R v.4.2.2 (R Core Team 2022) and the *R*-packages tidyverse v.2.0.0 (Wickham *et al* 2019), ggplot2 v.3.4.1 (Wickham 2016), sf v.1.0–14 (Pebesma 2018, Pebesma and Bivand 2023), rnaturalearthhires v.0.2.0 (South 2022), biscale v.1.0.0 (Prener *et al* 2022), patchwork v.1.1.3 (Pedersen 2023), and viridis v.0.6.4 (Garnier *et al* 2023).

3. Results

3.1. Nitrogen inputs and outputs

Denmark's agricultural systems had higher N inputs and outputs than Sweden's in total quantities and per unit agricultural area (figure 1). At national level, Sweden used 34% more synthetic N fertilizer than organic (manure) sources, whereas Denmark used 7% more organic N than synthetic. The average N deposition on agricultural land in Denmark (13.2 ± 1.0 kg ha^{-1} y^{-1}) was double that of Sweden (6.0 ± 1.1 kg ha^{-1} y^{-1}) (figure 1), with a South-North gradient (figures S1 and S2). Symbiotic N fixation in Sweden (19.8 ± 1.5 kg ha^{-1} y^{-1}) was about twice that of Denmark (9.2 ± 1.0 kg ha^{-1} y^{-1}). Total N outputs from croplands and grasslands were higher in Denmark (143 ± 10 kg ha^{-1} y^{-1} and 397 ± 30 kt y^{-1}) compared to Sweden (110 ± 13 kg ha^{-1} y^{-1} and 333 ± 37 kt y^{-1}). The most productive regions were found in East Denmark and South Sweden (figures S1 and S2).

Livestock production was larger in Denmark than in Sweden. The total feed N intake of livestock in Denmark was more than twice that of Sweden, with higher consumption in West Denmark (figures 1, S1 and S2). Denmark's total N in meat products was about four times greater than Sweden's (figure 1), while milk N output was about 1.8 times greater, with the highest values in West Denmark (figures S1 and S2). Manure N excretion was about half in Sweden (132 ± 1 kt N y^{-1}) compared to Denmark (260 ± 4 kt N y^{-1}), with Southern Sweden being the major production region (figures S1 and S2). The consistent farming practices in each country throughout our study period are reflected in the small standard deviation of N inputs and outputs (figure 1).

3.2. Nitrogen use efficiency

The NUE_{crop} showed a declining trend in Denmark from 2011 to 2020, while it remained stable in Sweden (figure 2(A)). The NUE_{crop} trends observed in Denmark and Sweden were negatively influenced by the drought in 2018, which reduced crop production (figure 2(A)). On average, Sweden had a higher national NUE_{crop} (0.72 ± 0.07) than Denmark (0.51 ± 0.04). In contrast, the $NUE_{livestock}$ has increased in both countries, with a more pronounced rise in Denmark (figure 2(A)). The average $NUE_{livestock}$ over the study period was 0.29 ± 0.005 for Denmark and 0.25 ± 0.004 for Sweden.

Western Denmark exhibits a lower NUE_{crop} than the rest of the country, with values ranging from 0.49 to 0.51 (figure 2(B)). In Northern Sweden, which has the smallest agricultural land and moderate livestock density (i.e. N ex-animal per agricultural land) nationally, we observed the highest NUE_{crop} (from 0.73 to 0.87) and lowest $NUE_{livestock}$ (from 0.16 to 0.20). Across all subnational regions in Denmark,

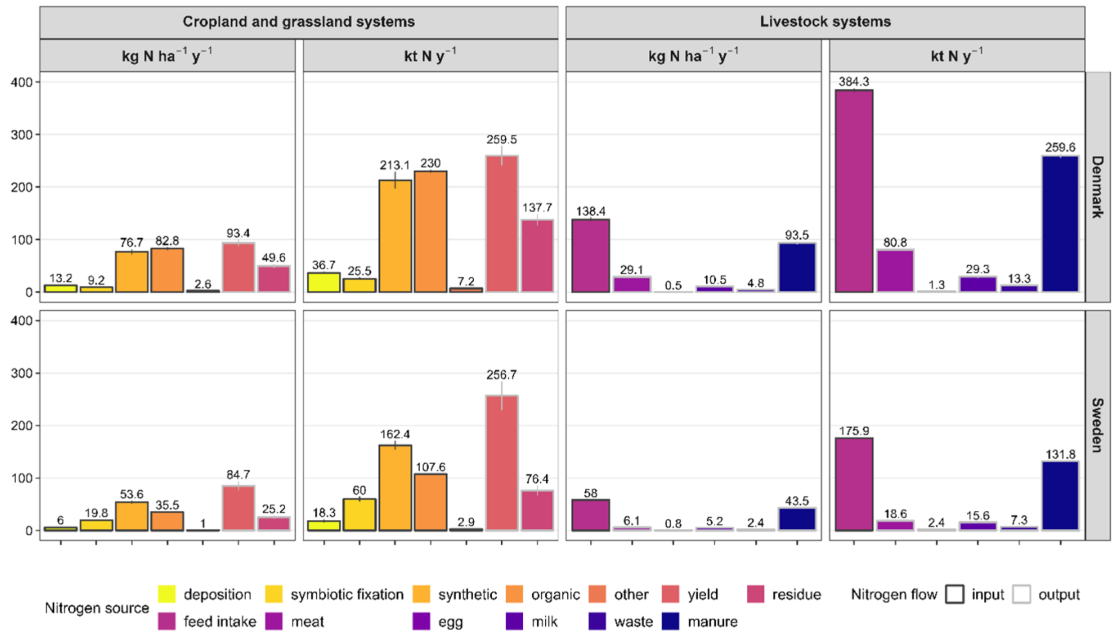

Figure 1. Average N inputs and outputs (kg N ha^{-1} y^{-1} and kt N y^{-1}) from the different sources of the agricultural systems in Denmark and Sweden (2011–2020). The values on top of the bars indicate the mean and the error bars, the standard deviation of the annual time series.

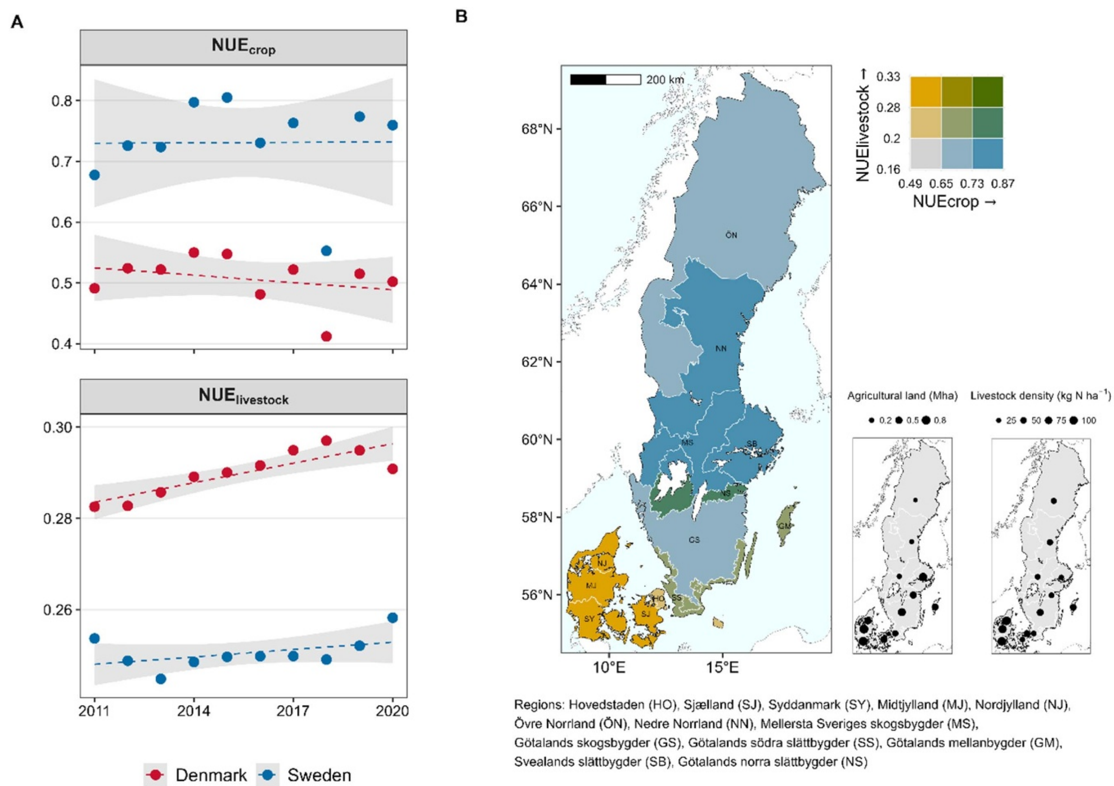

Figure 2. (A) Time series of NUE_{crop} and $NUE_{livestock}$ at national scale, including a linear trend fit and 95% confidence interval in grey and (B) spatial distribution of averaged NUE_{crop} and $NUE_{livestock}$ at subnational scale, with values classified based on their quantiles; the insets in (B) depict the average agricultural land and livestock density for the study period.

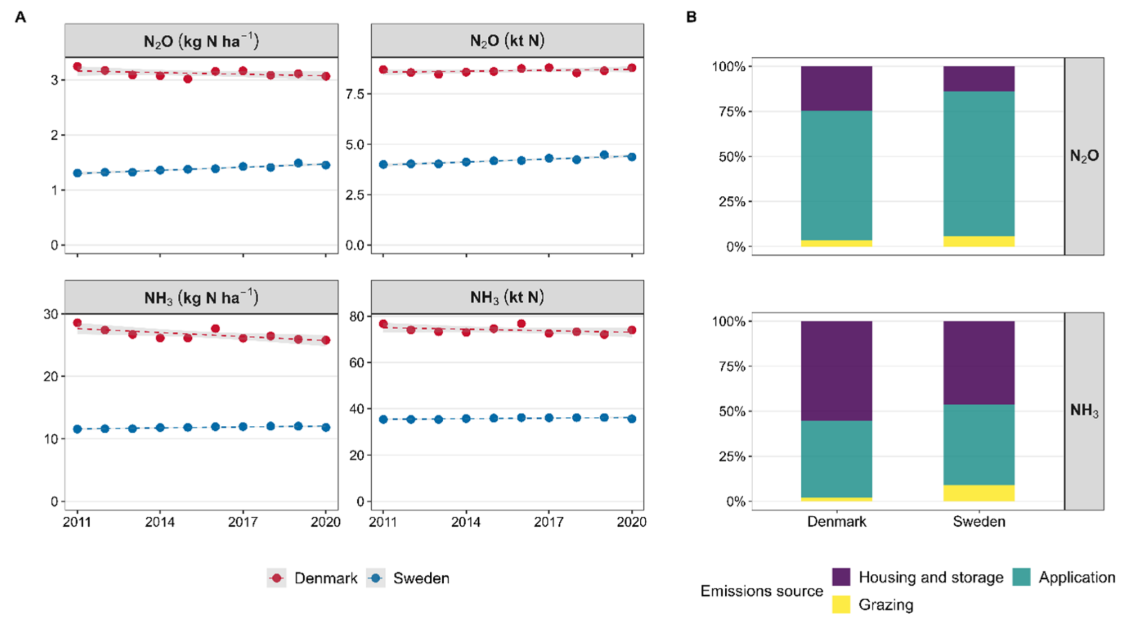

Figure 3. (A) Time series of N_2O and NH_3 emissions (kg N ha^{-1} and kt N), and (B) average distribution of main N_2O and NH_3 emissions sources (%) at a national scale.

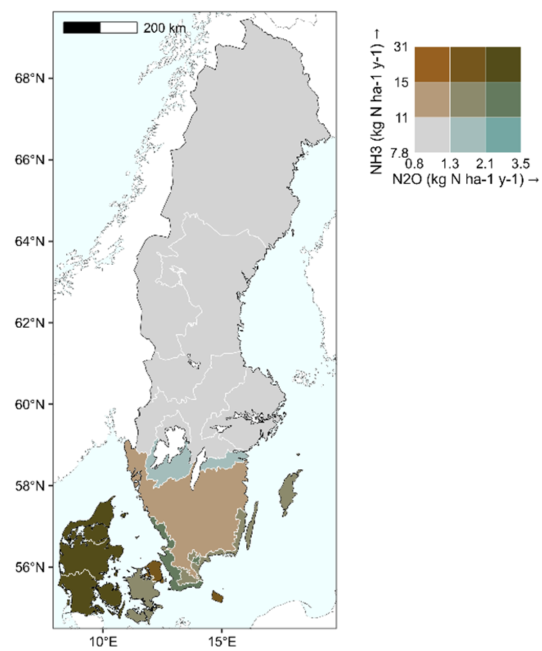

Figure 4. Spatial distribution of average N_2O and NH_3 emissions (kg N ha^{-1} y^{-1}) at a subnational scale, with values classified based on their quantiles.

$NUE_{livestock}$ values were higher than those in Sweden, ranging from 0.28 to 0.33, with only Southern Sweden showing comparable values (0.26).

3.3. Nitrous oxide and ammonia emissions

Denmark's total emissions of N_2O (8.7 ± 0.11 kt N y^{-1}) and NH_3 (74 ± 1.6 kt N y^{-1}) were approximately twice those in Sweden on average. Per agricultural area, Sweden emitted 56% less NH_3 and N_2O than Denmark. The gaseous N emissions only changed slightly during the years 2011–2020. The N_2O emissions increased slightly in Sweden, and Denmark experienced a decrease in NH_3 emissions (figure 3(A)). Using IPCC Tier 1 emission factors, the N_2O emission in Denmark averaged 3.7 ± 0.13 kg N ha^{-1} y^{-1} and 10 ± 0.42 kt N y^{-1}.

In Denmark and Sweden, most N_2O emissions occur after N fertilizer application (synthetic, manure, and other sources), accounting for 72% and 81% of total emissions, respectively (figure 3(B)). In Denmark, a slightly larger share of NH_3 emissions occur during housing and storage (55%) than in Sweden (46%). Conversely, the share of NH_3 emissions from grazing is higher in Sweden (9%) than in Denmark (2%).

West Denmark had the highest subnational emissions for N_2O (3.2–3.5 kg N ha^{-1} y^{-1}) and NH_3 (28–31 kg N ha^{-1} y^{-1}) (figure 4). Southern Sweden averaged 2.3 ± 0.07 kg N ha^{-1} y^{-1} for N_2O and 12 ± 0.26 kg N ha^{-1} y^{-1} for NH_3. A south-north gradient in N_2O emissions (kg N ha^{-1} y^{-1}) was observed in Sweden (figure 4), corresponding to the distribution of agricultural land and livestock density.

4. Discussion

4.1. Overview of nitrogen flows in Denmark and Sweden

Our analysis of N flows at subnational and national scales in Denmark and Sweden provides a detailed view of the agricultural N flows. Overall, crop and livestock production in Denmark are more intense than in Sweden due to higher inputs and outputs on smaller agricultural area (figures 1 and 2), which results in different agri-food systems. Livestock production is about twice as large in Denmark as in Sweden, primarily due to the large population of pigs and dairy cattle dominating the agri-food system. Consequently, there is greater livestock N excretion in Denmark (∼260 kt N y^{-1}) than in Sweden (∼132 kt N y^{-1}). In Denmark, the higher use of organic (manure) compared to synthetic N fertilizer (230 and 213 kt N y^{-1}) is induced by the high livestock density, increasing the risks of NH_3 emissions. In contrast, Sweden's greater reliance on synthetic fertilizers (162 vs. 108 kt N y^{-1}) reduces NH_3 emissions but increases N_2O emissions.

Our estimates show that symbiotic N_2 fixation is the fourth- and third-largest N input per unit of land in Denmark and Sweden, respectively. This input is particularly relevant in extensive regions with moderate livestock densities (e.g. Northern and Central Sweden). The added benefits of N-fixing plants, including improved soil health and fertility, could decrease the dependency on synthetic and manure N sources (Iannetta *et al* 2016).

The largest N flow in Denmark is animal feed intake, amounting to 384 kt N y^{-1}, with the highest subnational values in West Denmark (88–136 kt N y^{-1}), driven by the high pig and dairy cattle population in this region (Willems *et al* 2016); Denmark imports a significant amount of soybean from South America for animal feed (Osei-Owusu *et al* 2019). In term of trade of food commodities between Denmark and Sweden, Denmark exports pig meat and dairy products to Sweden, and imports beef and poultry (Horn *et al* 2022). Denmark's higher livestock density has resulted in greater N surpluses (138–98 kg N ha^{-1} from 2000–2010) compared to Sweden (59–46 kg N ha^{-1}) and other European countries (Svanbäck *et al* 2019). Although various mandatory regulations have reduced NO_3^- pollution and negative impacts of agriculture in Denmark (e.g. limits on N and phosphorus (P) application rates and nine months minimum slurry storage capacity) (Dalgaard *et al* 2014, Hoffmann *et al* 2020), further subnational action plans may be needed to further reduce N surpluses. In both countries, regulations limit livestock density based on P application rates, ensuring adequate agricultural area for manure spreading (Svanbäck *et al* 2019) and promoting good manure management (Swedish Board of Agriculture 2014, Aronsson and Johnson 2017). Indeed, integrated farming systems combining crops and livestock have the potential for better recycling of N waste materials (Bonaudo *et al* 2014, Lemaire *et al* 2014).

4.2. Nitrogen use efficeincy in Sweden and Denmark

The overall NUE_{crop} for Sweden (0.72) and Denmark (0.51) falls within the global range of 0.25–0.72, with both exceeding the global average of 0.42 for year 2010 (Zhang *et al* 2015). Sweden's higher NUE_{crop} than Denmark is likely due to a combination of factors, including Sweden's greater share of grass–clover leys in the crop mixtures, lower N input rates, and higher proportion of synthetic N fertilizer inputs, which are easier to match with crop demand than manure. Biases in NUE_{crop} estimates may also arise from uncertainties in symbiotic N fixation (Anglade *et al* 2015, Einarsson *et al* 2022). Einarsson *et al* (2021) reported higher NUE in croplands, averaging 0.68 for Denmark and 0.76 for Sweden from 2010 to 2019. These differences among studies stem from the varying data sources and N modeling assumptions (e.g. N concentration of inputs and outputs). Subnational NUE_{crop} levels were higher in North and Central Sweden than in other regions, mainly due to the predominance of grasslands and extensive farming practices. To further increase NUE_{crop}, there is a range of N management practices tailored to local conditions that could be considered, such as techniques for efficient use of manure and optimization of crop rotations (Zhang *et al* 2015, Bowles *et al* 2018, Hutchings *et al* 2020). Additionally, policies should include adaptation practices to mitigate extreme events like the 2018 drought, which lowered NUE_{crop} to 0.41 in Denmark and 0.55 in Sweden.

The $NUE_{livestock}$ has increased in Denmark and Sweden over the last decade. Denmark's $NUE_{livestock}$ is higher than Sweden's, primarily due to the greater proportion of monogastric animals (pigs), which have higher NUE than ruminants (Lassaletta *et al* 2016). The rising trend in $NUE_{livestock}$ in Denmark was mainly driven by the increase in milk production (from 26 kt N in 2011 to 32 kt N in 2020), which is produced more efficiently than other animal products in the country (Osei-Owusu *et al* 2019). The average $NUE_{livestock}$ in Denmark (0.29) and Sweden (0.25) are higher than recent estimates for Canada (0.23; Karimi *et al* 2020) and Ireland (0.23; Buckley *et al* 2016). Enhancing NUE in the livestock sector through improved breeding, feeding, and manure management holds significant potential in EU countries such as Denmark and Sweden (Leip *et al* 2022). With the widening scope of possible dietary changes, opportunities exist to reduce N losses through more efficient livestock production and reduced consumption of animal-source foods. The $NUE_{livestock}$ of a food system can be increased by shifting production and consumption to a higher share of animal products with high NUE, such as monogastric meat and dairy products (Groenestein *et al* 2019, Leip *et al* 2022). Decreasing ruminant-based production offers the co-benefit of reducing emissions associated with enteric methane (Crippa *et al* 2021). Reduced consumption of animal-source foods does not affect $NUE_{livestock}$ but would decrease N emissions from the food system as plant-based diets cause lower emissions (Xu *et al* 2021, Leip *et al* 2022).

4.3. Estimations of nitrous oxide and ammonia emissions

Our analysis revealed that Denmark emitted more N_2O compared to Sweden, primarily due to higher use of synthetic and organic (manure) N fertilizers and a higher amount of crop residues incorporated into the soil. We estimated Denmark's N_2O emissions at 8.7 kt N in 2011 and 8.8 kt N in 2020, which are similar to the national reports of 8.7–9.5 kt N for 2011 and 2020 (Nielsen *et al* 2023) when similar source categories are considered, but lower than 11 kt N in 2010 by Kros *et al* (2018). The differences among studies in Denmark arise mainly from using different emission factors (e.g. Tier 1 in the national inventory for soil N_2O emissions versus Tier 2 in our study). For Denmark, using Tier 1 IPCC factors (temperate regions) resulted in N_2O emissions that were, on average, 13% higher than Tier 2 estimates, primarily due to the higher emissions factors for synthetic fertilizer. For Sweden, our estimates for 2011 and 2020 ranged from 4.0 to 4.2 kt N, whereas the national report indicated 4.7–5.3 kt N for those years and similar emission categories (Swedish Environmental Protection Agency 2024). Also, the main reason for these differences is the use of different emission factors; Sweden's national reporting assumes 1% N_2O–N from manure and synthetic N fertilizers, while we used differentiated emission factors 0.6% and 1.6% (Hergoualc'h *et al* 2019). While N_2O emission factors at Tier 2 could be derived from scientific literature for Denmark (Petersen *et al* 2023a, 2023b), we used Tier 1 for Sweden due to limited information. This underscores the need for region-specific emissions factors to improve accuracy and study comparisons.

4.4. Drivers of emissions and potential for mitigation

The slight increase in Sweden's N_2O emissions is attributed mainly to the rise in synthetic N fertilizer use, from 154 kt N (2010) to 171 kt N (2020). We identified West Denmark and South Sweden as hotspots for N_2O emissions, as these are the main agricultural regions with higher subnational use of organic (manure) and synthetic N fertilizer, respectively. To mitigate N_2O emissions, these regions could employ strategies that have been found to be effective in reducing emissions, such as nitrification inhibitors (Peixoto and Petersen 2023, Tariq *et al* 2025), along with better documentation regarding the adoption of these practices for inventory purposes. Nitrification inhibitors could be particularly effective in reducing the N_2O emissions from the abundant pig slurry returned to the field in West Denmark (Peixoto and Petersen 2023).

Agriculture is responsible for 97% of NH_3 emissions in Denmark and 90% in Sweden (Nielsen *et al* 2024, Swedish Environmental Protection Agency 2024). Our analysis shows that Denmark emits more NH_3 from agriculture than Sweden, primarily due to its higher livestock population (dominated by pigs); the differentiated NH_3 Tier 2 emissions factors might contribute to the difference and variability of the emissions. Ammonia emissions from Denmark, excluding manure storage, were reported as 56–61 kt N y^{-1} by Kros *et al* (2018) and 51 kt N y^{-1} by Hutching *et al* (2014). In our study, NH_3 emissions were estimated as 74 kt N y^{-1} over the study period. National reports from Nielsen *et al* (2023) indicated NH_3 emissions ranging from 63 to 61 kt N y^{-1} for 2011–2020 when considering similar categories to our study. For Sweden, our estimates were 35 and 36 kt N y^{-1} in 2011 and 2020, while the national report indicates 37–38 kt N y^{-1} (Centre on Emission Inventories and Projections 2024). Differences in these estimates arise from varying modeling approaches, data availability, and emission factors.

West Denmark and South Sweden are NH_3 hotspots with high to moderate livestock densities, primarily dominated by pig and cattle production, respectively. In Denmark, farmers have implemented practices such as in-stable slurry acidification (e.g. up to 2.3% of fattening pigs in 2020), cooling (e.g. up to 4.2% of fattening pigs in 2020), and heat exchange for poultry (up to 90% in 2020), contributing to reduced NH_3 emissions. However, broader adoption of these technologies could further decrease emissions. These practices are not yet widely implemented in Sweden, but their adoption alongside complementary practices like in-field slurry acidification could abate NH_3 emissions. Given the diverse N management practices across regions, detailed activity data is essential for accurately reflecting farm variability at subnational and national levels, which is necessary to calculate and reduce N emissions.

4.5. Challenges and opportunities in nitrogen flow accounting

Subnational accounting of N can guide environmental policy on recycling N sources and reducing N emissions. However, as our study demonstrates, countries with different agri-food systems have relevant differences in the available data sources and models to estimate N flows, hampering intercomparison and reliable estimation. To improve the N flow accounting accuracy at subnational level, a harmonized system integrating relevant N data (e.g. FAOSTAT nutrient balances at national level (Ludemann *et al* 2024)) is needed, ideally with a broad international scope like the EU. Understanding the typology and heterogeneity of farming systems following a consistent methodological framework is vital for accurately quantifying the sources, emissions, and losses from farms to national scales.

Such a framework should ideally also be regularly revised to include N flux sources currently not well covered due to insufficient measurements, such as dinitrogen and nitrogen oxides emissions, and to incorporate Tier 2 and Tier 3 approaches. Furthermore, data sources could be revised to include activity data on the growing use of N-efficient technologies to treat manure and crop residues at the farm and field levels, such as slurry acidification, biogas production, and the use of nitrification inhibitors. This data will improve the accuracy of N flow accounting and NUE estimation, thereby reducing uncertainties for more effective N management and policy recommendations.

5. Conclusions

Our study provides subnational and national estimates of N flows, NUE, and major gaseous N emissions in Denmark and Sweden from 2011 to 2020. Sweden used less total N inputs and produced lower N outputs than Denmark. The main national differences were due to different geographic distributions of livestock and agri-food systems. The comparison of the two countries suggests that Sweden can improve its $NUE_{livestock}$ (subnational values between 0.16 and 0.26), while Denmark can enhance its NUE_{crop} (subnational values between 0.45 and 0.63). Denmark emits more N_2O and NH_3 than Sweden, in total quantities and per unit agricultural area, mainly due to higher soil N inputs, different livestock composition with a higher proportion of N from pig production, and more intensive agricultural practices. West Denmark and South Sweden were identified as N_2O and NH_3 emission hotspots. The overview of the main N flows can be used for monitoring the impacts of future policies designed to reduce N pollution and increase NUE at subnational and national scales.

Data availability statement

The data cannot be made publicly available upon publication because they contain sensitive personal information. The data that support the findings of this study are available upon reasonable request from the authors.

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Author contribution

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Conflict of interest

The authors declare no conflict of interest. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

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